

Pilot-Induced Oscillation Research: Status at the End of the Century

*Compiled by Mary F. Shafer and Paul Steinmetz
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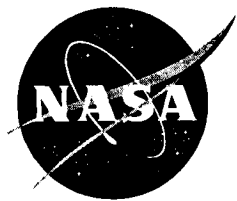
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National Aeronautics and
Space Administration

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Foreword

“Pilot-Induced Oscillation Research: The Status at the End of the Century,” a workshop held at NASA Dryden Flight Research Center on 6–8 April 1999, may well be the last large international workshop of the twentieth century on pilot-induced oscillation (PIO). With nearly a hundred attendees from ten countries and thirty presentations (plus two that were not presented but are included in the proceedings) the workshop did indeed represent the status of PIO at the end of the century.

These presentations address the most current information available, addressing regulatory issues, flight test, safety, modeling, prediction, simulation, mitigation or prevention, and areas that require further research. All presentations were approved for publication as unclassified documents with no limits on their distribution.

This proceedings include the viewgraphs (some with authors’ notes) used for the thirty presentations that were actually given as well as two presentations that were not given because of time limitations. Four technical papers on this subject that offer this information in a more complete form are also included. In addition, copies of the related announcements and the program are incorporated, to better place the workshop in the context in which it was presented.

Mary F. Shafer

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Session VI

Boeing T45
T45TS Ground Handling Characteristics
NASA Dryden Workshop



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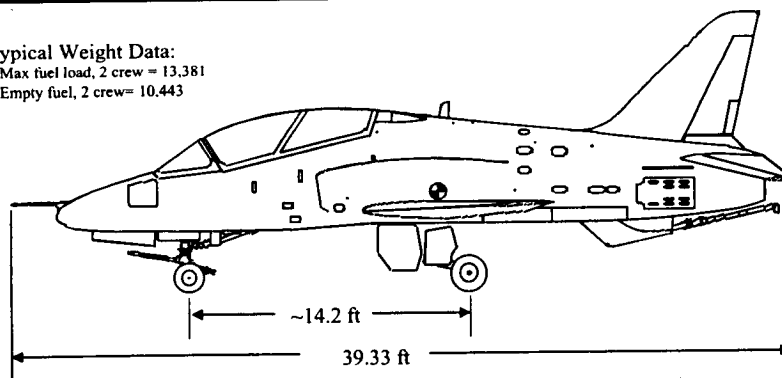
6-8 Apr 99

T45TS

T45 Aircraft Description
Derived from BaE Hawk



Typical Weight Data:
> Max fuel load, 2 crew = 13,381
> Empty fuel, 2 crew = 10,443



Key aircraft components:

- > ~12% of weight on nose landing gear
- > Single chambered, semi-levered main landing gear
- > Single chambered, cantilevered nose landing gear (2 tires)
- > 20 deg/sec nose wheel steering (NWS) - 12 deg defl max
- > Reversible, mechanical rudder
- > Hydraulic powered aileron, stabilator.
- > Limited Yaw Damper Control (YDC)

6-8 Apr 99



Directional control issues have been with the T45 since 1989. This is a basic airframe issue. Multiple "Triggers" such as cross-winds, inadvertent brake/NWS/rudder inputs, blown tire, aggressive corrections, etc. create a control problem which is amplified by "Sustainers" such as landing gear dynamics, brake sensitivity and feel, roll/yaw coupling, lateral acceleration cues, etc. Over the years many attempts and studies have been undertaken to improve basic airframe handling characteristics with some success. But fixes are not easy or "cheap". The lack of a good ground handling METRIC has dampened the enthusiasm to flight test "potential fixes".

6-8 Apr 99



- Nov 89 Established SA-4A during DT-IIA:
 - "Directional pilot induced oscillations during landing rollout."
- Nov 90 Developed current production NWS system
 - Full time NWS cleared "PIO" yellow sheet SA-4A
 - Entered Fleet Aug 92
- May 93 Established SA-162 during DT-II:
 - "Overly sensitive directional control characteristics during landing rollout."
- Dec 93 Developed 1st industry ground handling PIO metric
 - Provided a "yardstick" for predicting effectiveness of modifications
- Mar 94 ADR data @ KNAS supported PIO metric
- Mar 94 Started flight evaluation of higher rate NWS system
 - Improved handling but PIO susceptibility remained
- Jun 94 Joint USN/MDA "PIO team" formed to explore causes and solutions
- Sep 94 Recommended fix of high gain yaw damping with higher rate NWS
- Nov 95 Started flight evaluation of "PIO team" recommended fix
 - Concluded improvements not adequate for production
 - Identified objectionable ground handling other than PIO
- Jan 97 NAVAIR recommended assessment by outside company
- Aug 98 Started independent assessment with STI, subvendor to BA

6-8 Apr 99

T45TS

Boeing Criteria for Ground PIO Susceptibility



- Applied Mil STD criteria for longitudinal PIO (Ralph Smith).
 - Showed this to be a good predictor of directional PIO tendencies with:
 - > Frequency response of flight test data
 - > Six degree of freedom (6-DOF) analysis with 0.25 sec time delay pilot model
- MDA experience at this time:
 - 10 PA landings were analyzed - included a variety of pilots, crosswinds, and braking tasks.
 - > Ny at pilot and yaw rate (R) considered most significant control parameters
 - > Bode plots: 0.6 Hz control from Ny feedback, 1.0 Hz control from R feedback
 - A015 landing rollout PIO shows pilot "responding" to Ny
- Criteria successfully predicted higher rate NWS would not reduce PIO potential.
- Employed as metric for joint USN/Boeing PIO Susceptibility team
 - Goal: Achieve F-18 Ny phase response.
 - Identified 50 potential causes. 8 most promising showed no single or combined root cause.
 - Analyzed 3 augmented control solutions:
 - > R + Ny feedback to NWS, R command, and R feedback to rudder
- R feedback to rudder met F-18 Ny phase criteria.

Improved, high rate PWM NWS and YDC-10 approved for flight test.

6-8 Apr 99

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Results Of YDC-10 Flight Test Program



Steering Control Electronic Set (SCES) 1.4

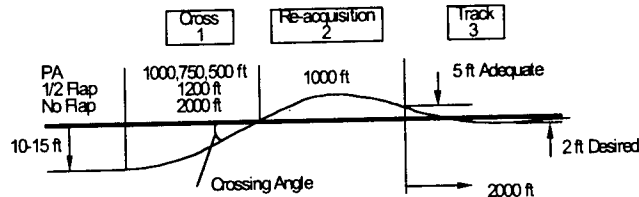
- Allowed testing of production and "test" software with a bit flag change.
- Production T45 NWS software:
 - Bang-bang controller, 20 deg/sec max no-load rate
 - Turn-on at 0.75 deg error, turn-off at 0.5 deg error.
 - Low gain steering: linear slope, 2.5 inches of pedal -> 12 deg of NWS
- Pulse Width Modulation (PWM) software:
 - Still a bang-bang controller, but
 - > 5 discrete no-load rates, from 8 deg/sec to 52 deg/sec
 - > Uses "look-ahead" to determine best control speed
 - > Narrows turn-on/turn-off threshold when pedals moving
 - > Variety of pedal -> NWS schedules available

NOTE: PWM also required a hydraulic supply orifice change to achieve higher no-load rate.

6-8 Apr 99



Centerline Crossing Task



CROSS

- Low gain and low predictability
- Significant variations in crossing angle
- YDC tends to washout initial input

RE-ACQUISITION

- High gain, high accelerations/rates
- Susceptible to "roll/yaw"
- Steeper x-ing angle, harder task, prone to centerline overshoot

TRACK

- High gain, low Ny, moderate yaw rate
- Performance degraded if Phase 2 overshoots desired criteria

Combined with other variations (weight, crosswind, inadvertent differential braking), significant run-to-run variations in task difficulty can occur.

6-8 Apr 99



• FREQUENCY DOMAIN ANALYSIS

- Predicted reductions in Ny phase lag were achieved
 - > Only for small inputs (~25%) due to yaw damper saturation
- High rate NWS had no effect on Ny or R phase lag
- Centerline x-ing maneuver did produce PIOs during Re-acquisition and Tracking
 - > ONLY with non-optimum YDC feedback gain
 - > Re-acquisition PIOs: High Ny -> roll/yaw
 - > Tracking PIOs: Low Ny -> often ignored in pilot comments

• PILOT COMMENTS

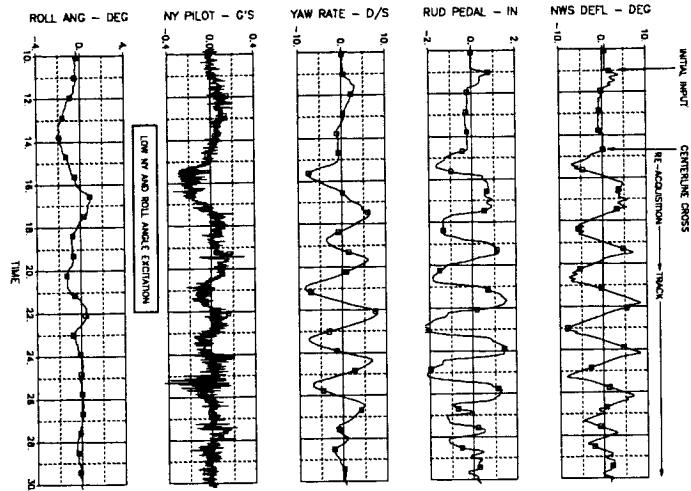
- PIO ratings slightly reduced with YDC/PWM.
- Significant factors other than phase lag influencing the pilot:
 - > Velocity vector loosely coupled to nose
 - > Roll opposite yaw - "leans"
 - > Inadvertent NWS inputs
 - > Insufficient brake pedal (force) feedback
 - > Rudder pedal mechanical characteristics
 - > Crosswinds

CONCLUSIONS: Incremental improvement for small pedal inputs only, and would not close yellow sheet SA-162.

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T45TS

Results Of YDC-10 Flight Test Program

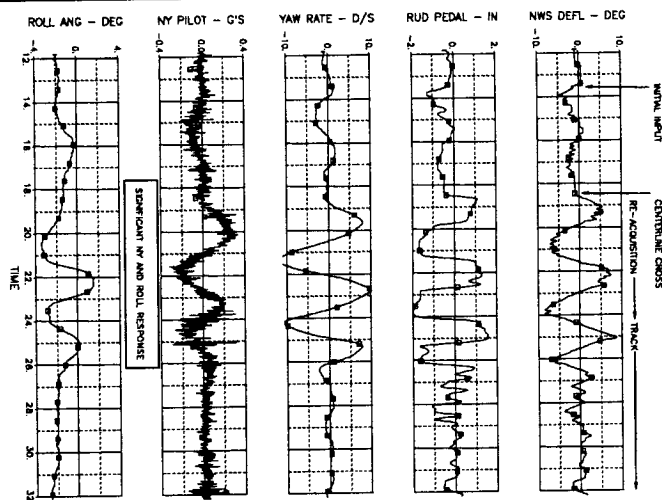


YDC-10 DYNAMIC AIRCRAFT RESPONSE
PRODUCTION NWS, WITH YDC GAIN AT 2.5
750 FT CENTERLINE CROSSING MANEUVER
SYM AC 143588 FLIGHT 878 RUN 17 TASK 2

6-8 Apr 99

T45TS

Results Of YDC-10 Flight Test Program



YDC-10 DYNAMIC AIRCRAFT RESPONSE
PRODUCTION NWS, WITH YDC GAIN AT 2.5
500 FT CENTERLINE CROSSING MANEUVER
SYM AC 143588 FLIGHT 878 RUN 21 TASK 2

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NASA LaRC Analysis of T45 Tires



- **METHOD:**
 - Used **Low speed Tire Test Vehicle (LTTV)** to measure cornering performance of nose and main tires under full scale, realistic surface conditions.
 - > Max vertical load 6000 lb
 - > Max tire yaw angle 90 deg
 - > Max speed 60 mph
 - Varied tire pressure (field, carrier), vertical load and skid angle.
 - Nose tire is very under-loaded at 300-900 lb per tire (5-6% vs. design 32%).
 - LTTV data validated by flight test trajectory matching.
- **CONCLUSION:**
 - Main tire cornering stiffness less than modeled by 13-44%, depending on normal load.
 - Main tire cornering stiffness reduction with normal load more than currently modeled.
 - Nose tire cornering stiffness more than modeled by 6-19%, depending on normal load.

A ground handling assessment **REQUIRES** accurate tire data under realistic surface conditions. The LTTV proved to be a rapid and economical tool for gathering T45 tire data. Other NASA facilities exist for tires with greater vertical loadings.

6-8 Apr 99

T45TS

Independent Assessment Contract With STI



- **Objective and Product:**
 - Analytical assessment by Systems Technology Incorporated (STI)
 - Recommend procedures and/or aircraft modifications with the potential to minimize or eliminate undesirable landing rollout characteristics.
 - Feasible recommendations will likely require additional research and flight evaluation by USN/BA team prior to production consideration
- **Tasks:**
 - Review past efforts
 - Examine basic aircraft design issues
 - Recommend a way forward
- **Status:**
 - 7 Feb 98 - USN issued RFP to Boeing (BA)
 - 21 Apr 98 - BA selected STI as winning subvendor
 - 21 Jul 98 - USN/BA complete contract negotiations
 - 20 Aug 98 - Kickoff meeting in STL. BA, STI & NAVAIR (15 month contract)
 - 16 Nov 98 - First quarterly review
 - 18 Feb 99 - Second quarterly review
 - 15-19 Feb 99 - First flight simulation

6-8 Apr 99

T45TS

Independent Assessment Contract With STI Status After First Flight Simulation



- NASA LARC tire data incorporated into all 6-DOF models.
- Analysis of flight test data suggest that heading angle feedback is the primary pilot control mechanism.
- Boeing 6-DOF and STI linear model have been benchmarked to flight test data.
- STI Linear model analysis shows that the T45 -
 - has an oversteer characteristic (tire cornering stiffness is key)
 - has a critical speed, above which the vehicle has an unstable pole (~ 60 kts).
- The understeer gradient UG may be a reliable metric for PIO potential

$$UG = 32.17 * 57.3 * \left\{ \left(\frac{m}{l} \right) * \left[\left(\frac{b}{Y_{af}} \right) - \left(\frac{a}{Y_{ar}} \right) \right] \right\} \quad \begin{matrix} [\text{deg/g}] \\ [\text{slugs}] \\ [\text{ft}] \\ [\text{ft}] \\ [\text{ft}] \\ [\text{lb/rad}] \\ [\text{lb/rad}] \end{matrix}$$

m = vehicle mass
 a = distance from front tire to cg
 b = distance from rear tire to cg
 l = distance from front to rear tire (l=a+b)
 Y_{af} = front axle "aero+tire+..." cornering coefficient
 Y_{ar} = rear axle "aero+tire+..." cornering coefficient

6-8 Apr 99

T45TS

Independent Assessment Contract With STI Status After First Flight Simulation



- Maneuvers used during first simulation:
 - Constant radius turn circle (2000 ft)
 - Maximum heading capture and stabilization (aggressive)
 - Heading capture and hold (instruments only - no visual)
 - Heading angle sum-of-sines tracking (instruments only - no visual)
 - Runway centerline tracking with crosswind gust disturbance
- Aircraft parameters varied during first simulation:
 - Fuel (empty, 65% full)
 - Aircraft understeer gradient, UG
 - Nose wheel steering actuator model (production and "ideal")
- Preliminary findings:
 - Fixed base simulation: not perfect, but we're working on it
 - "Ideal" actuator model: most effect on fine tracking, not PIO
 - Turn circles show a break in roll vs. Ny at 0.2 g's (approx 2 deg roll)
 - HQR and PIO ratings track understeer gradient UG
 - A 2 point HQR/PIO reduction may be possible with a tire change

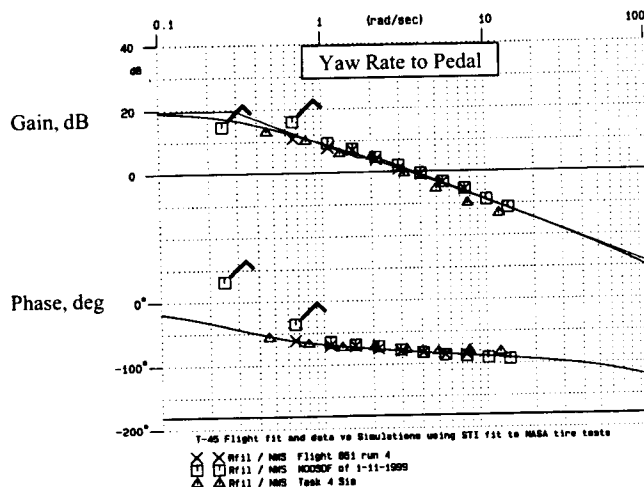
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Independent Assessment Contract With STI Status After First Flight Simulation



Excellent agreement between flight test, flight simulation and Boeing 6-dof (MODSDF)



Low Power
in
Flight Test Data

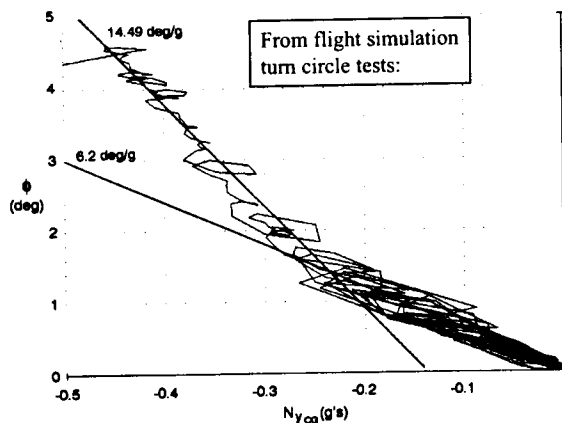
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Independent Assessment Contract With STI Status After First Flight Simulation



From flight test: More than 2 deg of roll was consistently remarked as "very uncomfortable".
Below 2 deg of roll, it was often ignored.



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Independent Assessment Contract With STI Status After First Flight Simulation

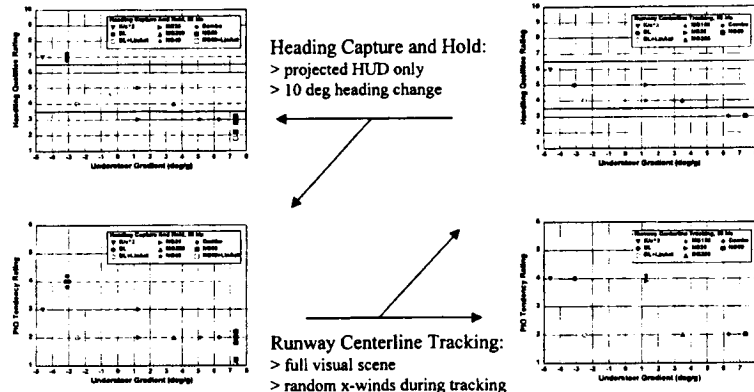


Figure 1. HQR and PYOR versus Understorey Gradient for the Hanging Capture and Hold Trap

Figure 3. HQA and PROB versus Underflow Gradient for the Railway Corridor Tracking Test.

6-8 Apr 99

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Independent Assessment Contract With STI Future Efforts



- Refine Boeing flight simulation
 - Adjust seat/pedal/heel-rest to T45 spec
- Pilot-vehicle analysis:
 - Acquire flight test data from dissimilar aircraft
 - Complete pilot-vehicle analysis of ground handling dynamics:
 - > Ergonomics (braking, steering crossover)
 - > Control sensitivity and magnitude
 - > Crosswinds
- Refine tasks/metrics to quantify expected improvements
 - Define new, or modify existing tasks.
 - Quantify possible “improvements” in flight simulation
- Present final report/recommendations: November, 99

6-8 Apr 99

EXTRACTION OF PILOT-VEHICLE CHARACTERISTICS FROM FLIGHT DATA IN THE PRESENCE OF RATE LIMITING

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Systems Technology, Inc.

David G. Mitchell
Hoh Aeronautics, Inc.

Pilot-Induced Oscillation Research:
The Status at the End of the Century
NASA Dryden Flight Research Center
6-8 April 1999

PRESENTATION OUTLINE

- Program Overview
- Background
 - Category II PIOs
 - Airplane Bandwidth/Phase Delay Criteria
- F-14 Dual Hydraulic Failure Flight Test Program
 - Flight Test Data Description
 - Flight Test Data Analyses
- Conclusions

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PROGRAM OVERVIEW

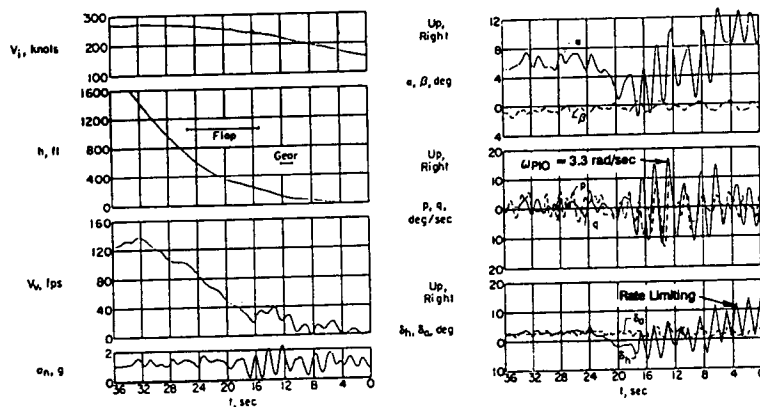
- Work performed by Systems Technology, Inc. (STI) under a subcontract from Hoh Aeronautics, Inc. (HAI)
- Part of a HAI Phase II SBIR with the Air Vehicles Directorate of the Air Force Research Laboratory
- Air Force Project Engineer - Thomas J. Cord
- F-14 flight data provided by Naval Air Warfare Center, Aircraft Division

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TIME HISTORY OF THE X-15 LANDING/FLARE PIO



Ref. NASA TN D-1057

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CATEGORY II PIOs

- Essentially nonlinear pilot-vehicle system oscillations with amplitudes well into the range where rate and/or position limits become dominant
- Transitional category between Category I and the most general, nonlinear Category III PIOs
- Most common jump-resonant, limit-cycle, PIO event
- Intrinsically severe PIOs

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CATEGORY II ISSUES

- Presence of rate limiting and other nonlinearities result in a Frequency and Amplitude dependence
- There are, therefore, a task dependent family of solutions that will determine PIO susceptibility
- Rate and/or position limiting within a closed-loop structure will disrupt the aircraft augmentation as the limiter becomes active
- Criteria will be inherently more complicated in their application
- Ready applicability of criteria may imply a need for specific software applications

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CATEGORY II FLIGHT DATA

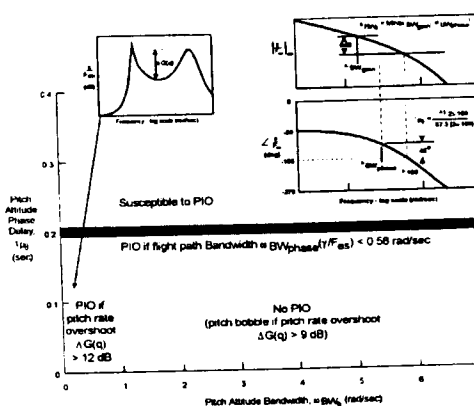
- All candidate criteria are tentative until validated with flight data (qualitative & quantitative)
- Until recently available flight data has been extremely limited and incomplete (essentially time histories from flight test of developmental aircraft)
- HAVE LIMITS (USAF TPS Class 96B)
 - Configurations flown with variable stability NT-33A
 - Reference AFFTC-TR-97-12 (approved for public release)
- USAF TIFS Study
 - Parallel HAVE LIMITS with large aircraft configurations

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BANDWIDTH/PHASE DELAY REQUIREMENTS



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BANDWIDTH/PHASE DELAY

- Use flight derived frequency response (nonlinearities included) to compute Bandwidth (ω_{BW}) and Phase Delay (τ_p) parameters for a variety of input amplitude levels
- Assume linear requirements apply to nonlinear (quasi-linear) configurations at each input amplitude
- A Bandwidth/Phase Delay locus that is a function of input amplitude is overlaid on the linear requirements to define PIO-prone regions
- The input amplitude conditions (A_i) corresponding to the boundary crossing of the $[\tau_p, \omega_{BW}](A_i)$ locus indicates a critical region for possible onset of Category II PIO

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BANDWIDTH/PHASE DELAY (concluded)

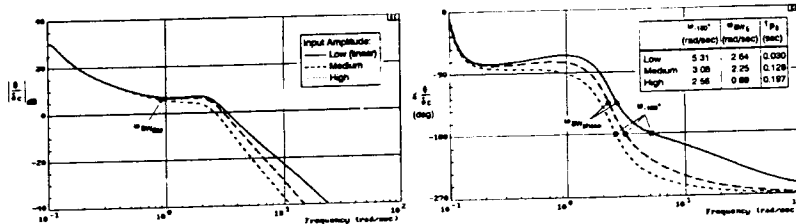
- The transition from a phase margin bandwidth condition to a gain margin bandwidth condition can be indicative of a Category II jump resonance phenomenon
- A systematic approach to specify pilot input magnitude for conducting frequency sweeps is needed
- Drops in coherence occur whenever power is present in the output that does not correspond to the PVS input, such as pilot-induced noise (remnant), sampling harmonics, and nonlinearities
- Analysis of available data often indicates a reduction in describing function coherence in the neighborhood of the onset or saturation frequency of the rate limiter

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DESCRIBING FUNCTION VARIATIONS WITH INPUT AMPLITUDE

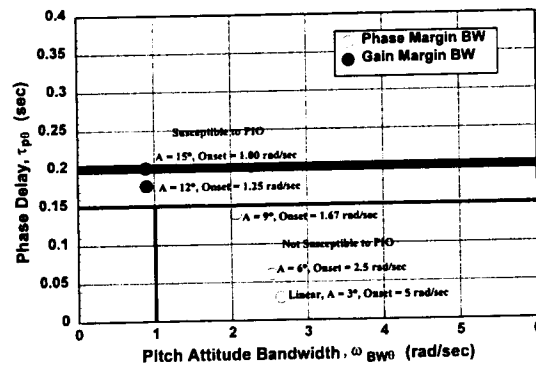


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BANDWIDTH/PHASE DELAY INPUT AMPLITUDE SENSITIVITY



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F-14 DUAL HYDRAULIC FAILURE FLIGHT TEST PROGRAM

- Navy flight test program was conducted from 10/90 to 3/91.
- The back-up flight control module (BUFCM) was evaluated for in-flight refueling and landing.
- Maximum stabilator rates were 10 and 5 deg/sec for BUFCM-HIGH and BUFCM-LOW modes, respectively.
- Aircraft demonstrated good handling in formation flight.
- A number of PIOs were encountered during in-flight refueling, drogue tracking, and offset field landings.
- An excellent PIO database was inadvertently created.

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FLIGHT TEST DATA ANALYSES

- Flight Test Data Description
- Example Time Histories
- Identification of Stick Dynamics
- Effects of Rate Limiting
- Identification of PIO Frequency and Task Bandwidth
- Airplane Bandwidth/Phase Delay Assessments

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FLIGHT TEST DATA DESCRIPTION

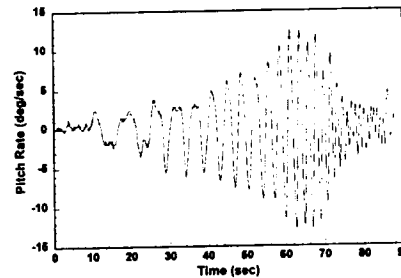
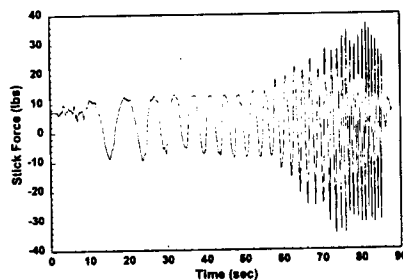
- High quality time history data for:
 - 7 frequency sweeps
 - 8 drogue hook-ups
 - 2 drogue tracking runs
 - 1 field offset landing
- Runs were characterized by:
 - Aircraft configuration: wing sweep, gear and flap positions
 - Flight condition: altitude, airspeed, Mach number
 - FC mode: SAS On, SAS Off, BUFCM-HIGH, BUFCM-LOW

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BUFCM-HIGH FREQUENCY SWEEP TIME HISTORIES

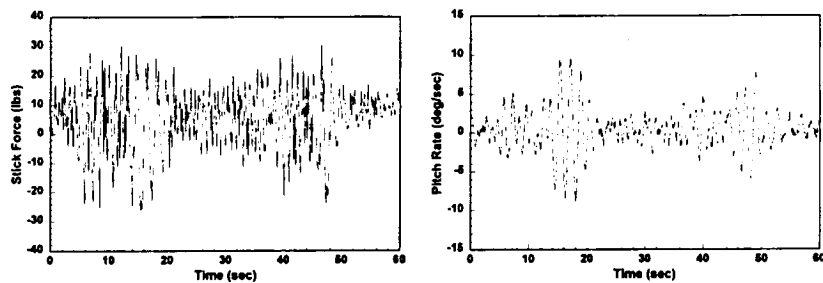


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BUFCM-HIGH DROGUE TRACKING TIME HISTORIES

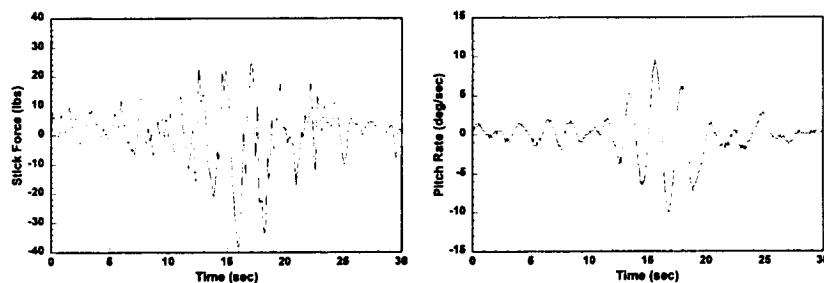


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BUFCM-HIGH DROGUE HOOK-UP TIME HISTORIES

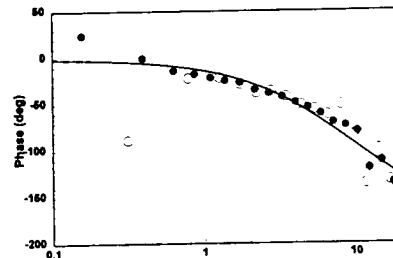
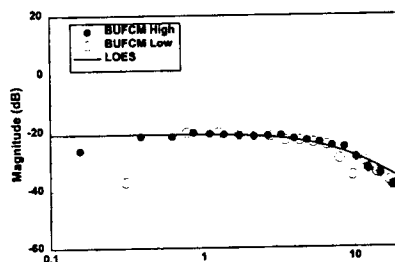


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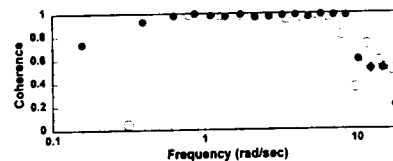
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LONGITUDINAL STICK DYNAMICS



$$LOES = \frac{\delta_{LON}}{F_{LON}} = \frac{42.7 \times 10^{-3}}{2.546 \times 83.15}$$

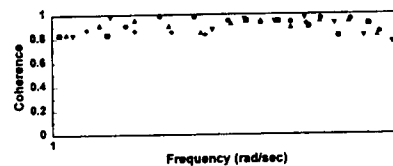
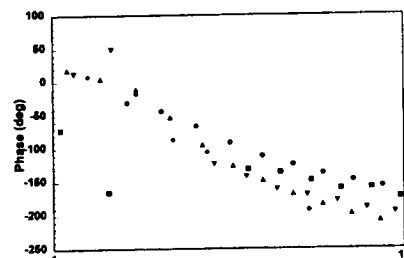
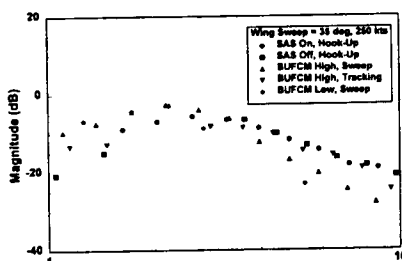


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EFFECTS OF RATE LIMITING ON q/F_{LON}

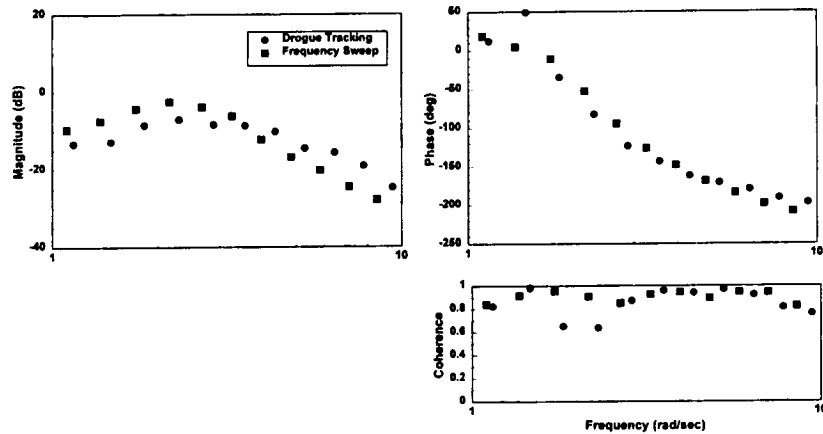


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BUFCM-HIGH q/F_{LON} CASE COMPARISON

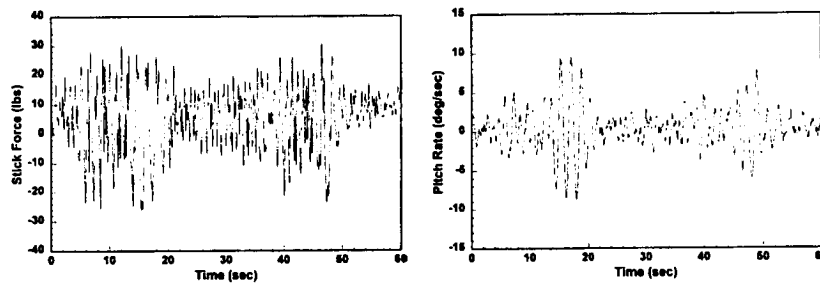


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BUFCM-HIGH DROGUE TRACKING TIME HISTORIES

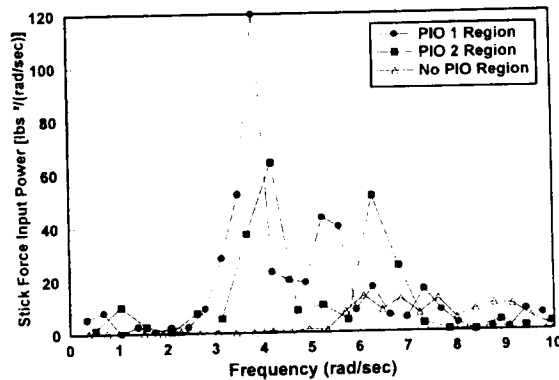


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PILOT INPUT PSD FOR BUFCM-HIGH DROGUE TRACKING

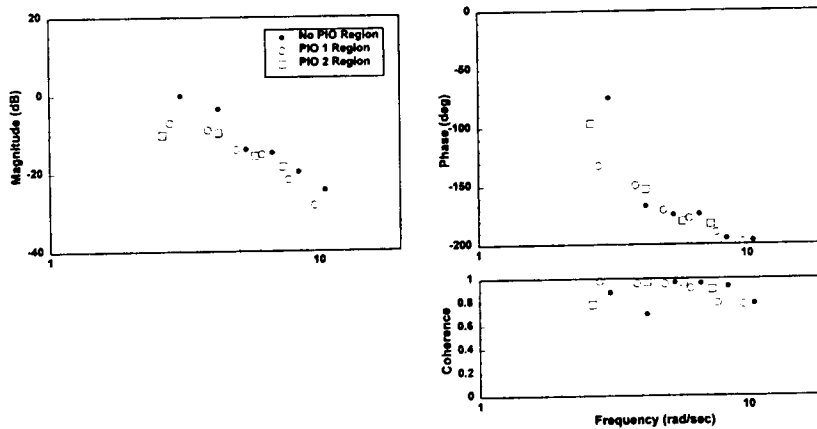


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q/F_{LON} FREQUENCY RESPONSES FOR BUFCM-HIGH DROGUE TRACKING

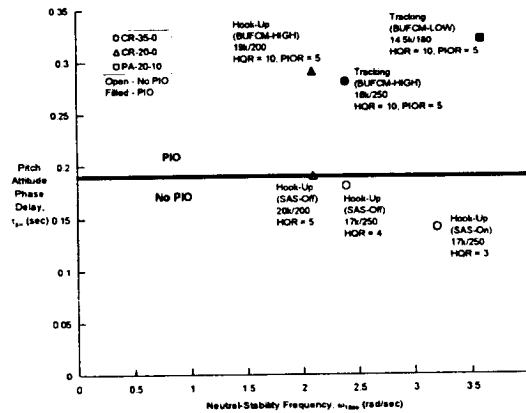


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PIO PHASE DELAY REQUIREMENT



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CONCLUSIONS

- Frequency domain analysis techniques were successfully applied to flight test data to obtain describing functions in the presence of rate limiting.
- Results display the expected magnitude reduction, significant additional phase lag, and input amplitude sensitivity associated with rate limiting.
- Frequency sweeps and drogue tracking runs allowed for best extraction of PVS characteristics.

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CONCLUSIONS

- PIO frequencies and task bandwidths were identified from the pilot input PSDs.
- Excessive phase delay due to rate limiting led to PIO for both drogue hook-up and tracking tasks.
- Results from the analysis of the flight test data support the application of Bandwidth/Phase Delay criteria for the prevention of PIO.

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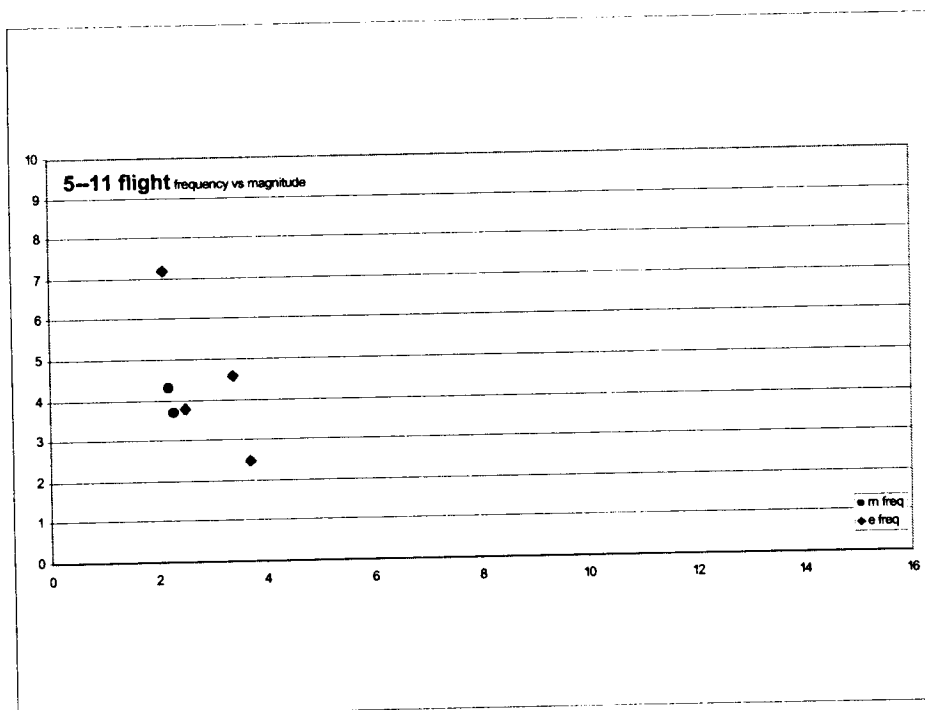
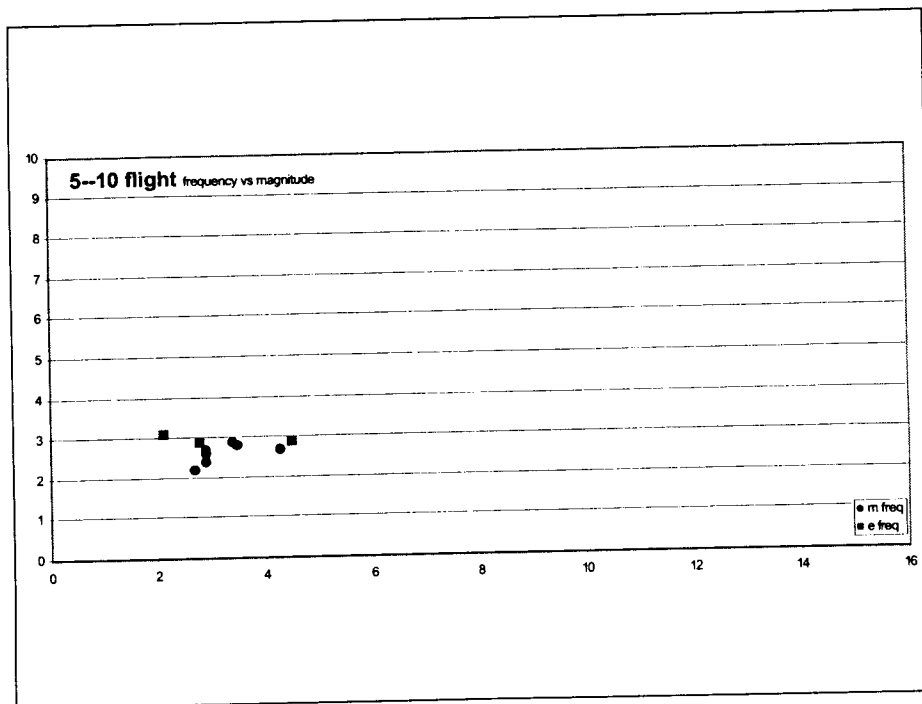


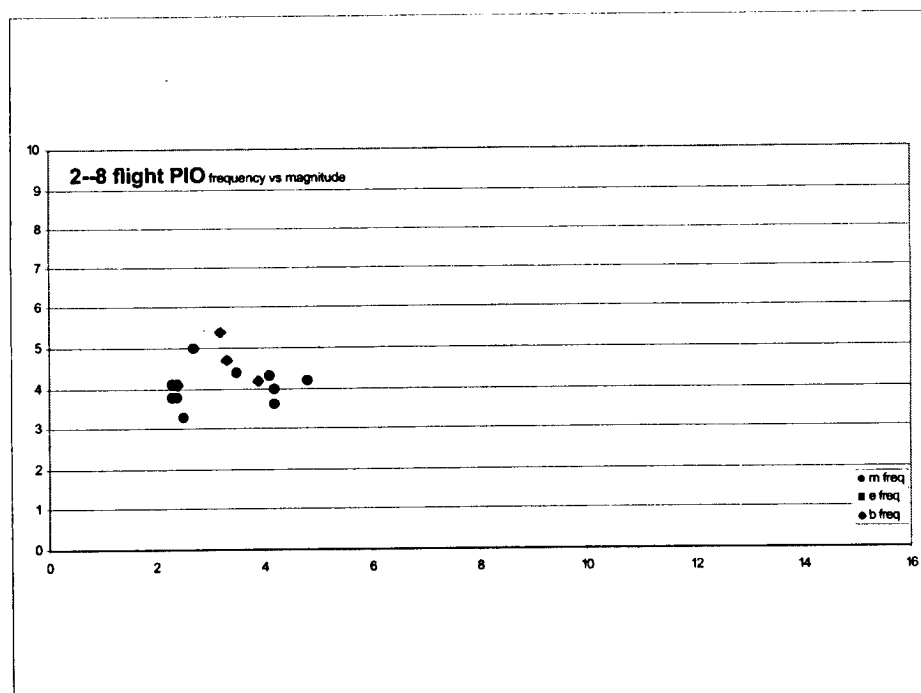
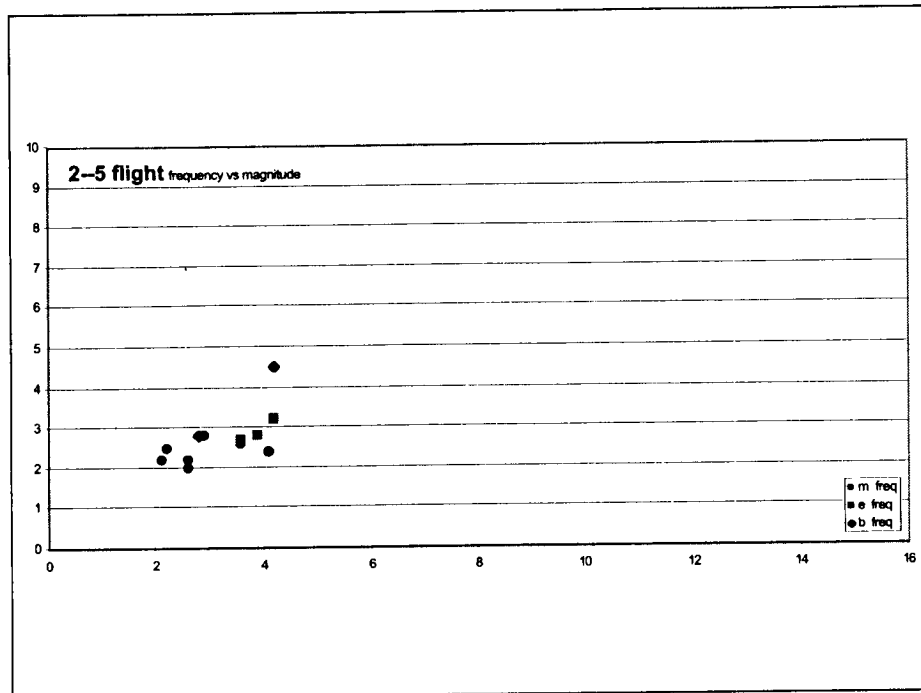
COMPARISON OF PIO SEVERITY FROM FLIGHT AND SIMULATION

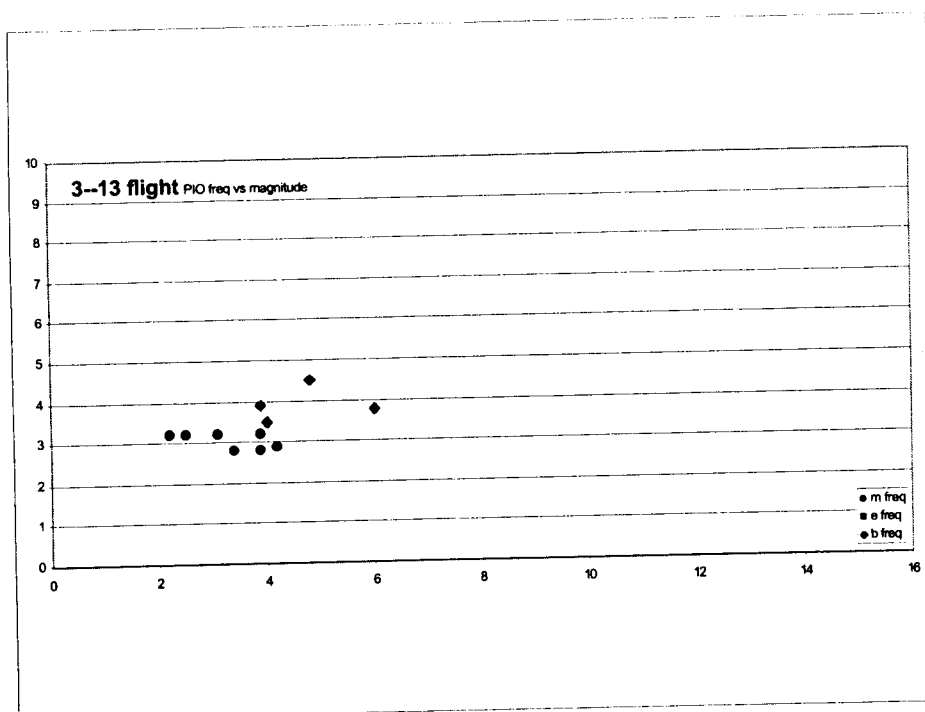
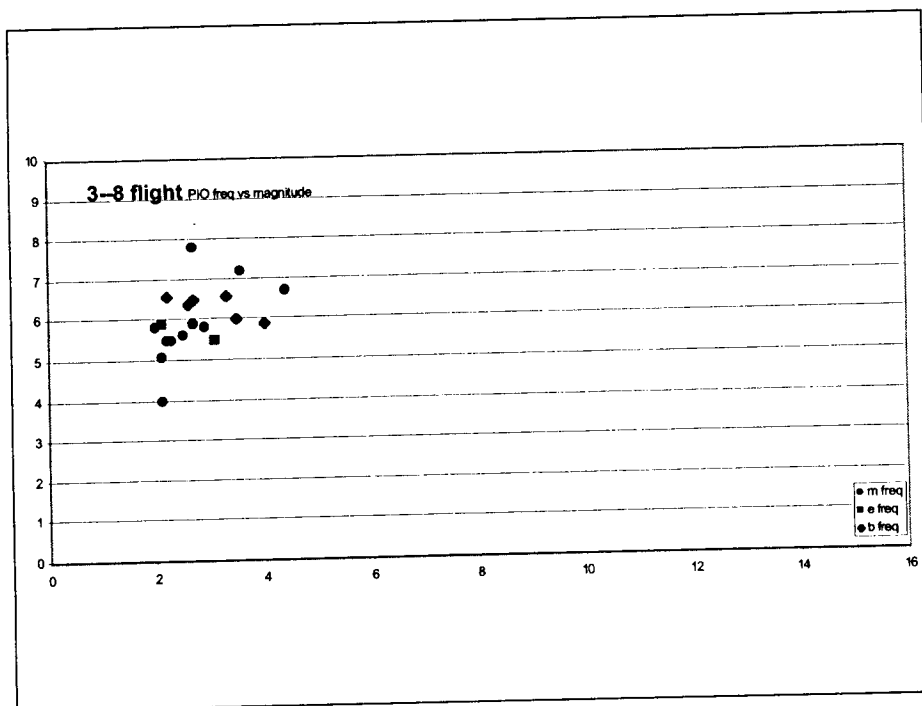
Thomas J. Cord
AFMC/AFRL/VAAD
NASA PIO WORKSHOP
APRIL 1999

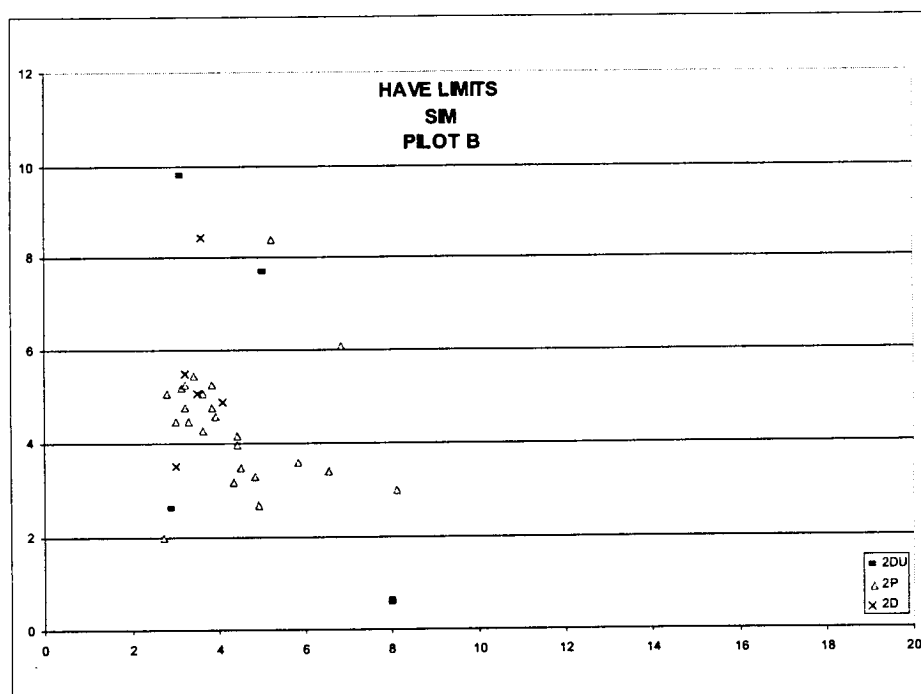
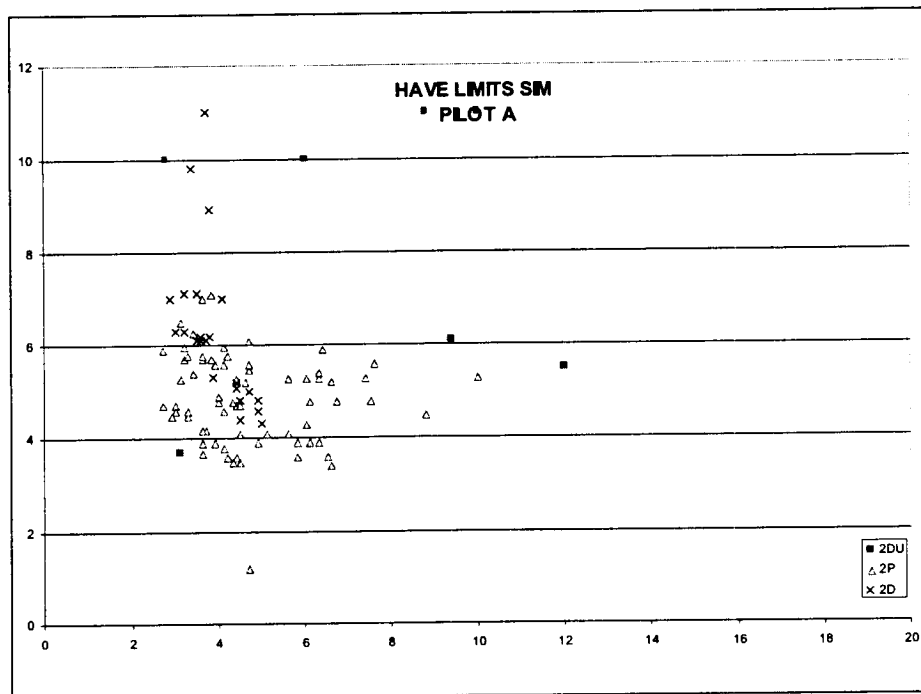
PIO FREQUENCY AND MAGNITUDE

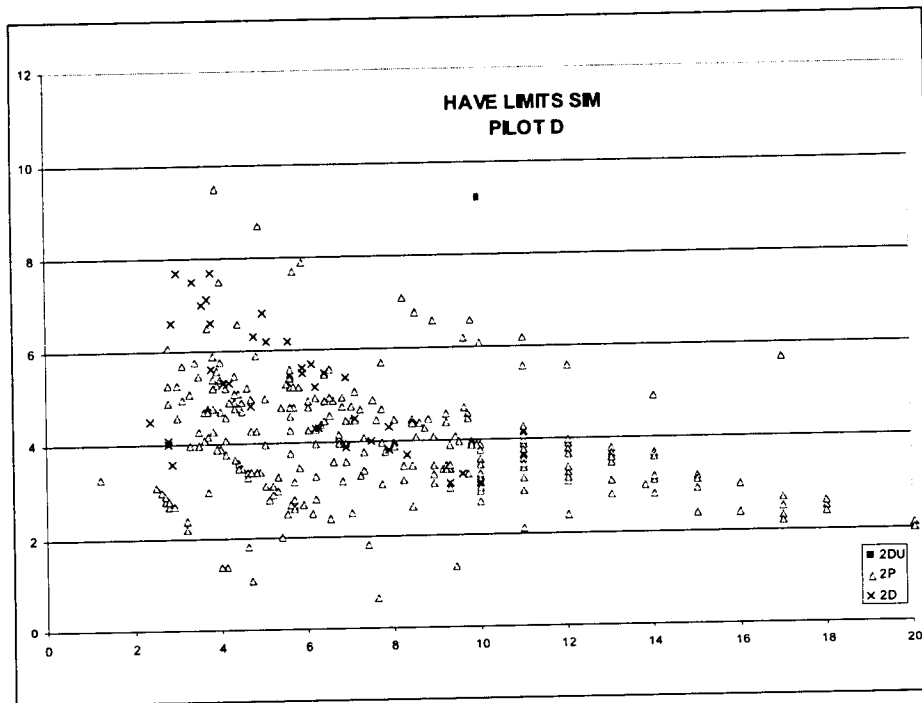
- PILOT CONSISTENCY
 - FLIGHT
 - SIMULATION





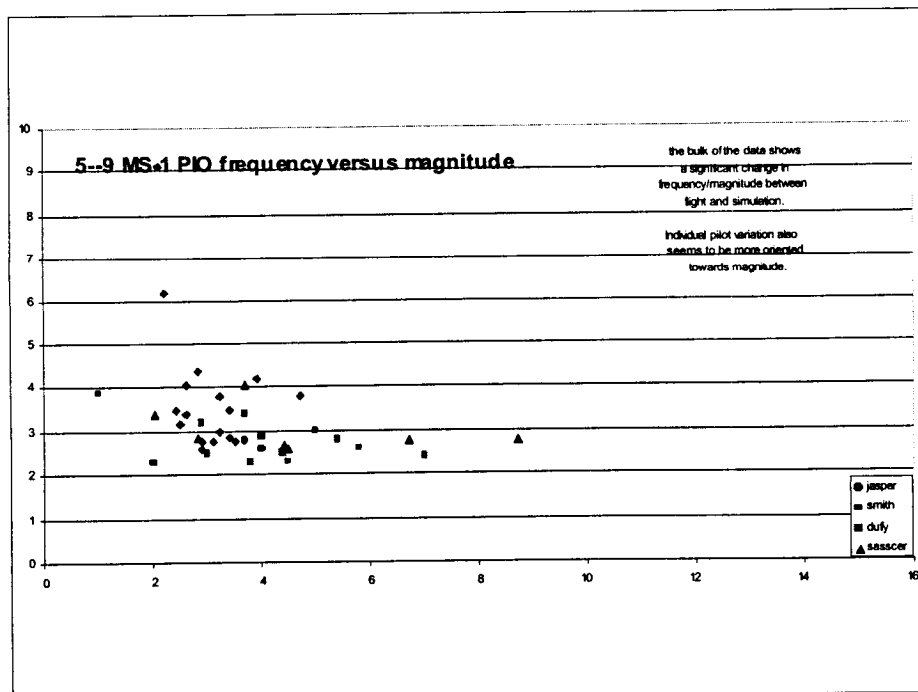
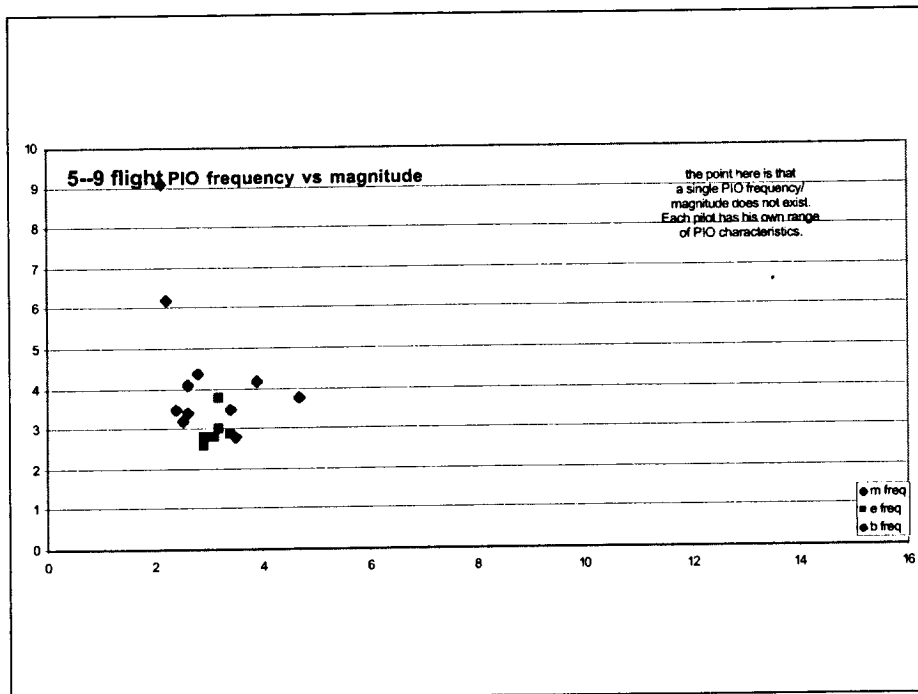


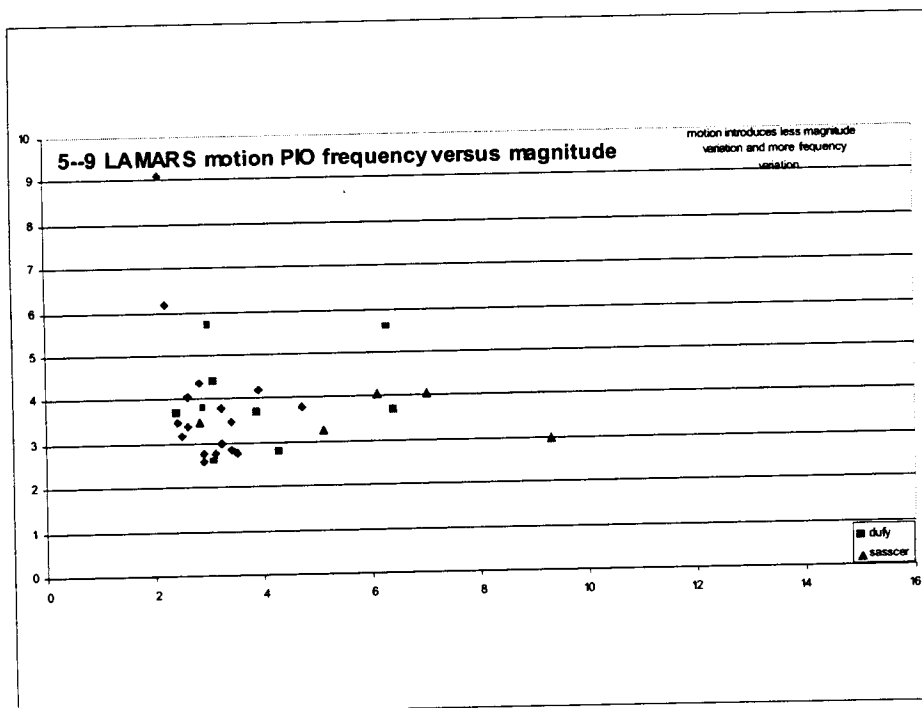
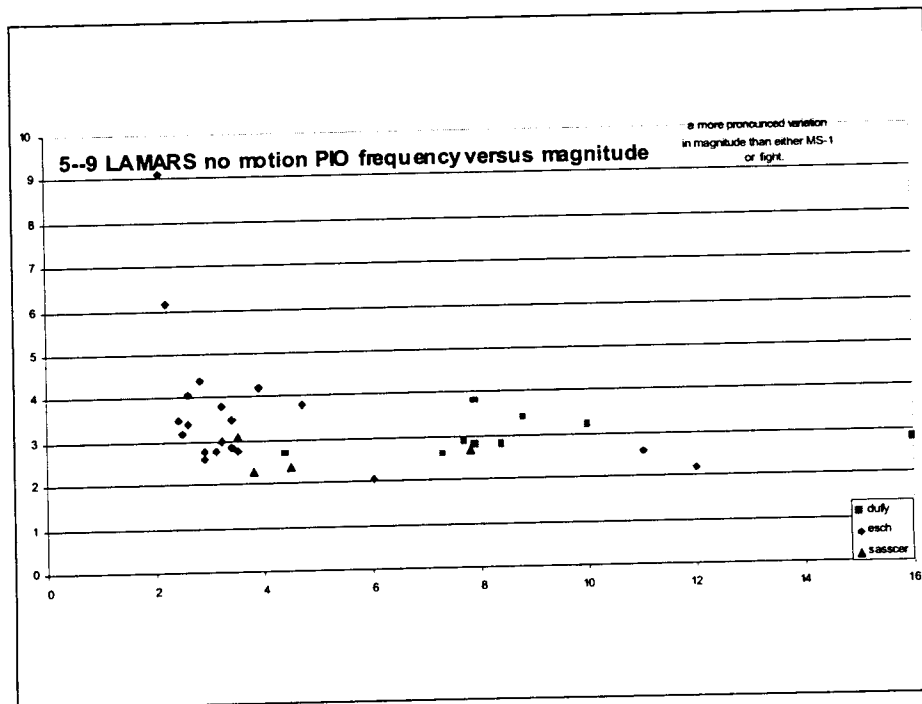




PIO FREQUENCY AND MAGNITUDE

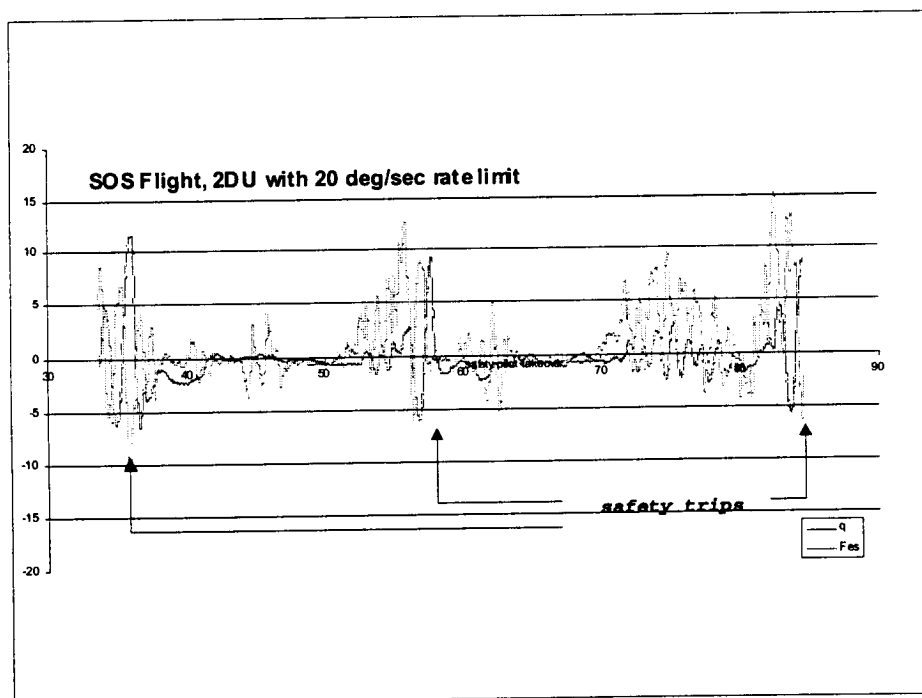
- EFFECT OF SIMULATION ENVIRONMENT

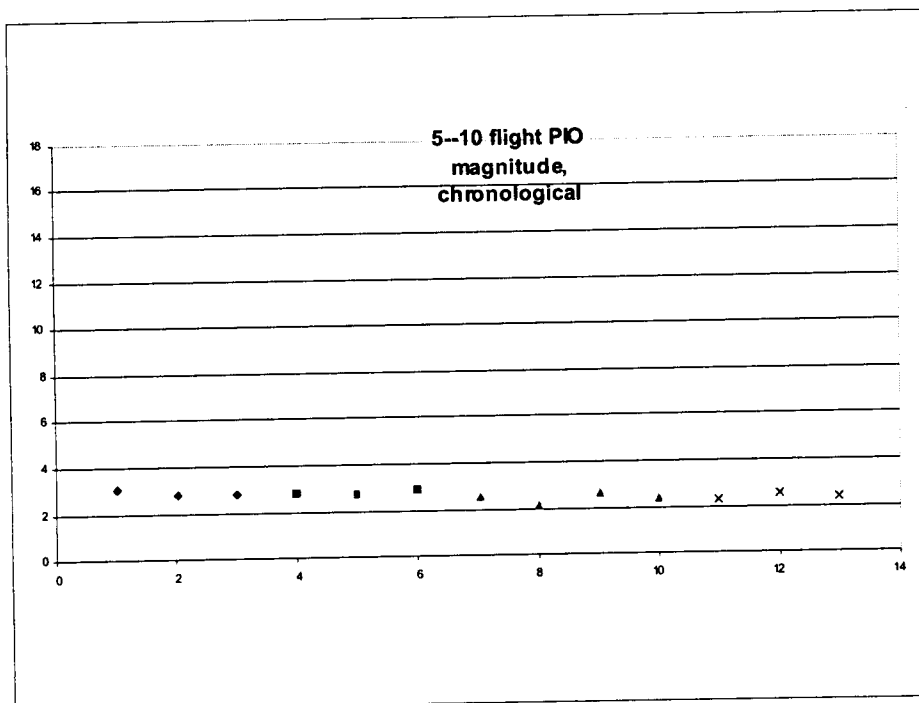
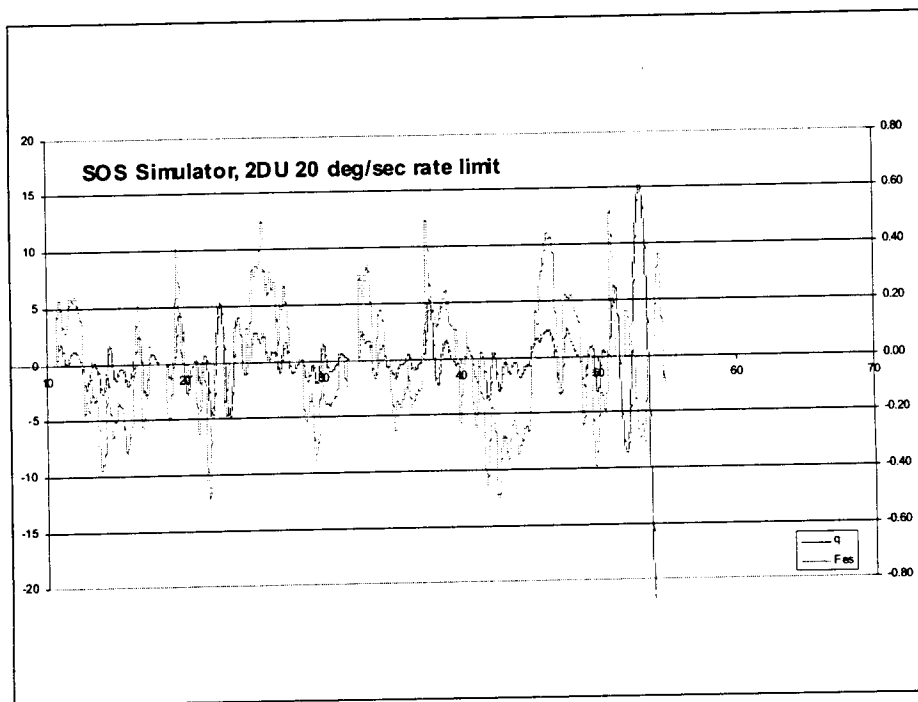


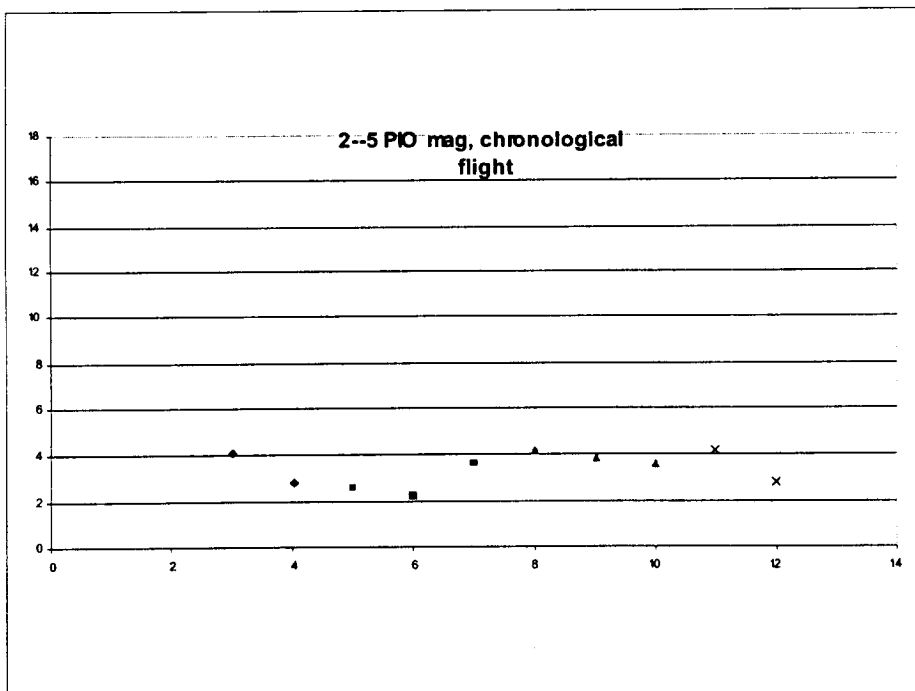
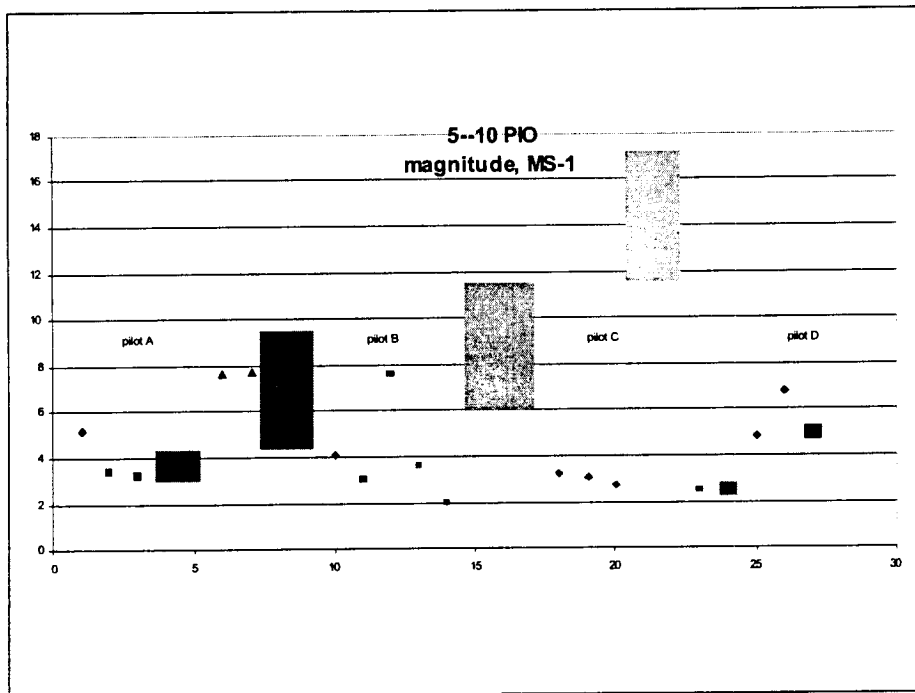


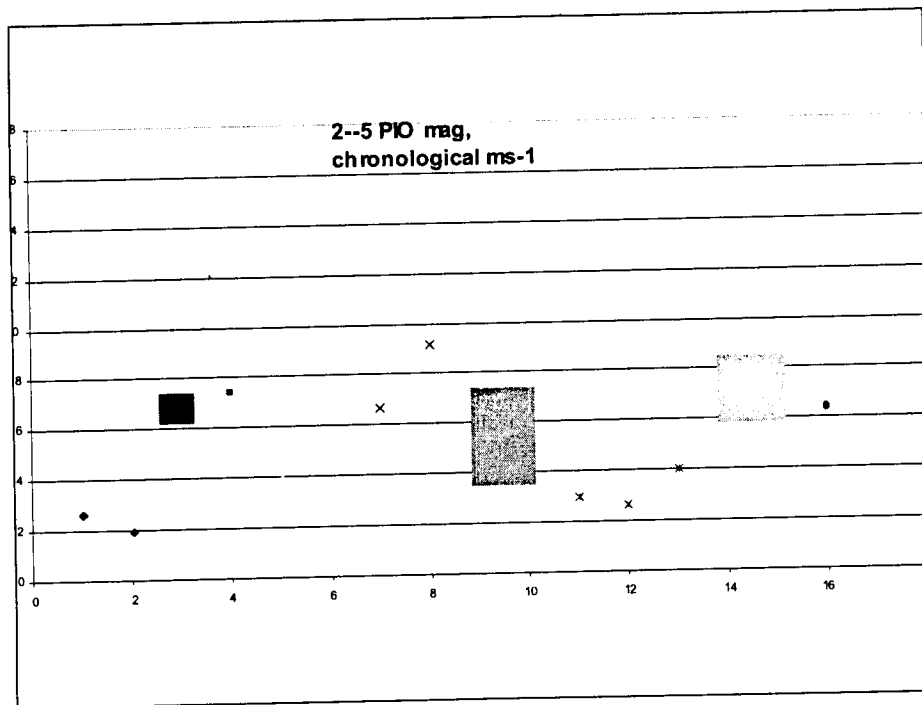
TIME HISTORY ILLUSTRATIONS

- GROWTH OF PIO MAGNITUDE
- INFLUENCE OF SAFETY PILOT









OTHER OBSERVATIONS

- INFLUENCE OF PREVIOUS RUN
- INFLUENCE OF KNOWLEDGE THAT TEST IS FOR PIO

PIO TRIGGERS

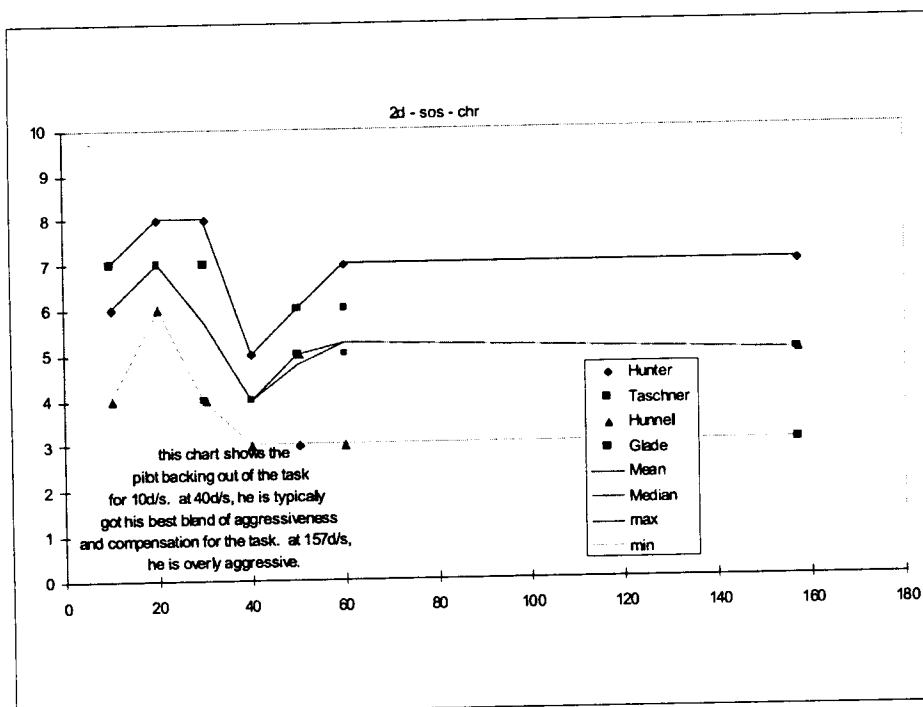
- **FLIGHT: NOMINAL TASK PROVIDES TRIGGER**
- **SIMULATION: ARTIFICIAL STIMULUS MAY BE REQUIRED**

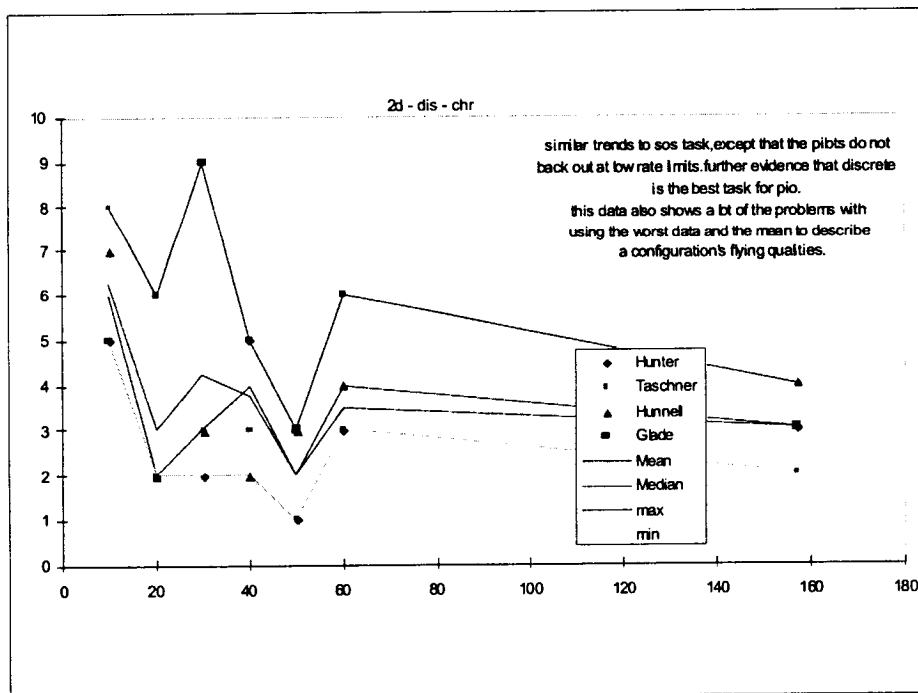
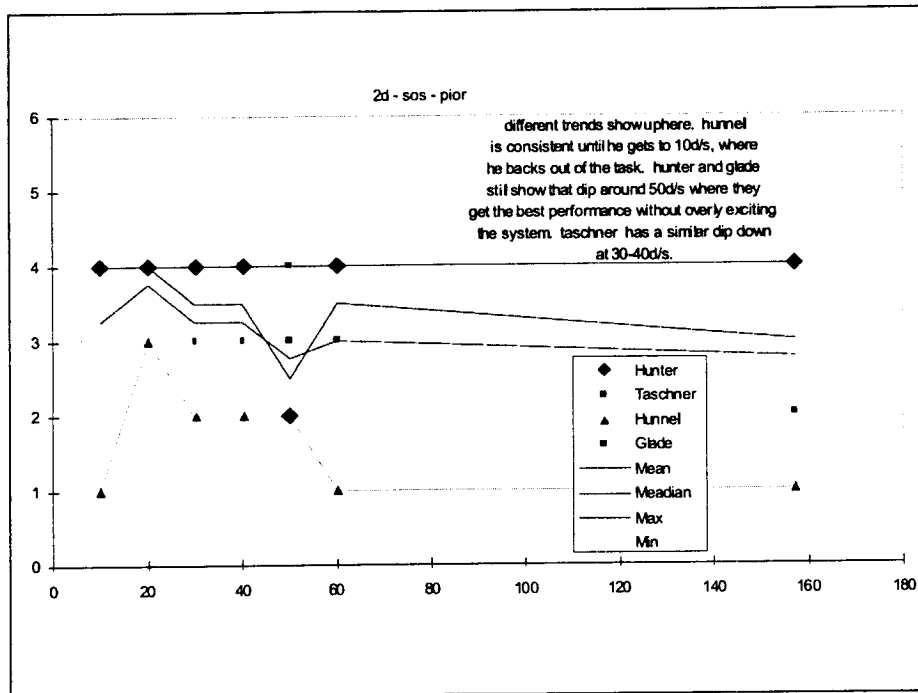
SUMMARY

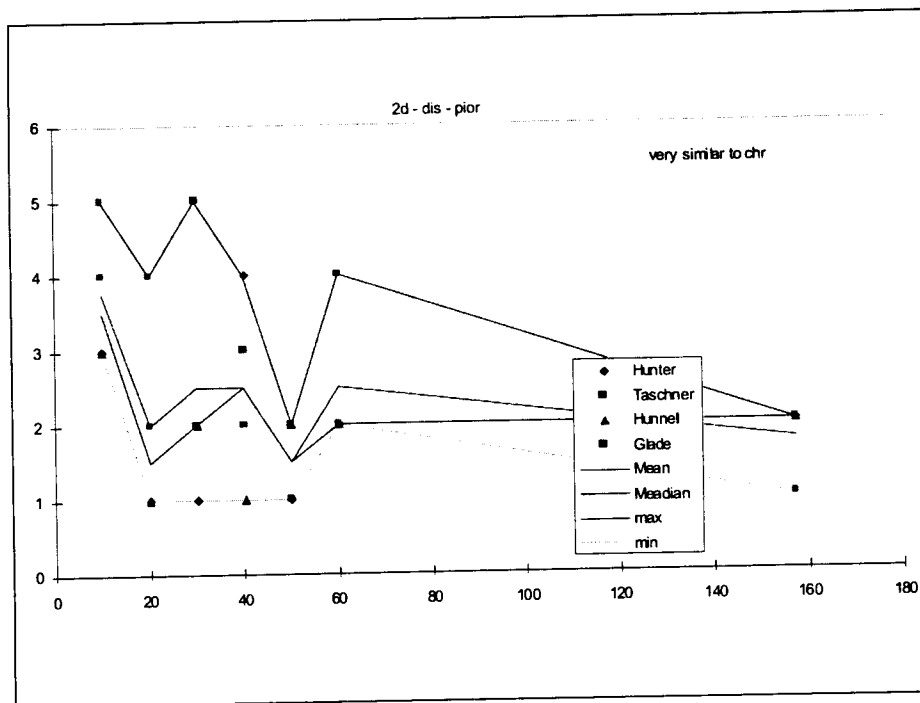
- **EFFECT OF MOTION - MINIMUM CHANGE IN RATINGS, NOTICEABLE IN PHYSICAL CHARACTERISTICS**
- **SAFETY PILOT - ENDS TASK SOONER, MAY AFFECT MAGNITUDE**
- **EVALUATION TASK - KNOWLEDGE OF PIO TEST MAY INFLUENCE RESULTS, ARTIFICIAL TRIGGER SHOULD BE CONSIDERED.**
- **PIO FREQUENCY - A RANGE NOT A NUMBER**

FLYING QUALITIES GROUP

- ~1952 Air Force Control Laboratory
- ~1962 Air Force Flight Dynamics Lab
- 1979 Air Force Wright Aeronautical Laboratory
- 1989 Wright Research and Development Center
- 1991 Wright Laboratory
- 1998 Air Force Research Laboratory
- 1999 deceased (no FQ research office)







A Summary of the Ground Simulation Comparison Study (GSCS) For Transport Aircraft

**PIO Workshop at NASA-Dryden
April 6-8, 1999**

**Terry von Klein
Stability, Control, & Flying Qualities Group
Boeing - Phantom Works, Long Beach**



GSCS Goals

- **Fly a Test Transport Aircraft**
 - Degraded FCS Configurations
 - Evaluate Pilot Induced Oscillation (PIO) Characteristics

- **Evaluate Identical Configurations in Simulation**
 - PIO Characteristics
 - Motion & Fixed-Base Ground Simulation

- **Compare Flight Vs. Simulation**



PHANTOM WORKS

Stability, Control & Flying Qualities

Test Facilities

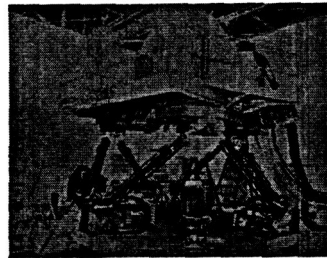
- **Modern, High Wing Transport Test Vehicle**

- Specialized, One-of-a-Kind Test Aircraft
- Fly-By-Wire Flight Control System
- Change-A-Gain (CAG) System



- **Motion-Base Simulator**

- Tuned to Test Vehicle
- Validated Math Models



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PHANTOM WORKS

Stability, Control & Flying Qualities

FCS Configurations

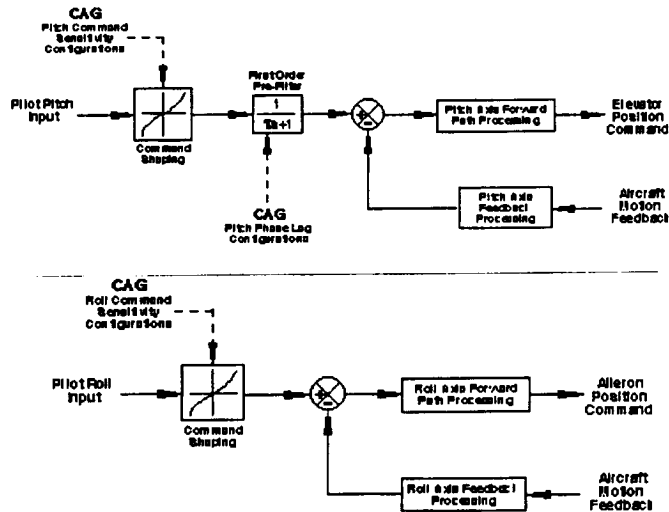
FLIGHT CONDITION	FCS CONFIGURATIONS	HANDLING QUALITIES EFFECTS
High Speed Cruise Condition (285 KIAS, Clean Wing, 25000 ft.)	Pitch Phase Lag	Add Up to 100 msec of Extra Time Delay in Pitch Response
	Pitch Command Sensitivity	Increase Pitch Response to Pilot Input By a Factor of 2.0
Low Speed Power Approach Condition (145 KIAS, 12000 ft, Flaps & Gear Down)	Pitch Phase Lag	Add Up to 100 msec of Extra Time Delay in Pitch Response
	Pitch Command Sensitivity	Increase Pitch Response to Pilot Input By a Factor of 2.0
	Roll Command Sensitivity	Increase Roll Response to Pilot Input By a Factor of 2.2

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PHANTOM WORKS

Stability, Control & Flying Qualities

Pitch/Roll CAG Locations



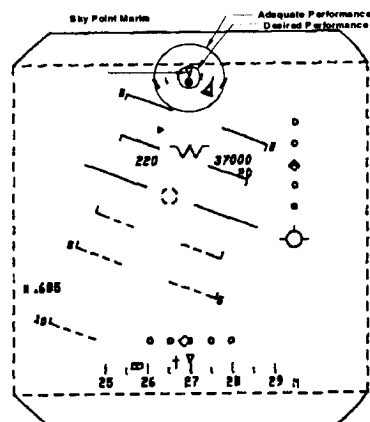
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PHANTOM WORKS

Stability, Control & Flying Qualities

High Speed Evaluation Task

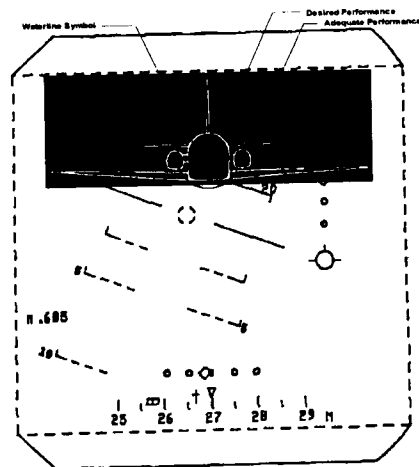
- Boom Tracking Behind Tanker Aircraft
- Separation Distance of Approximately 1 Plane Length
- Pre-Defined Scripts of Boom Movement
- Feet on the Floor



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Low Speed Evaluation Task

- **Formation Trail Task Following a Small Leader Aircraft**
- **Separation Distance of Approximately 2 Plane Lengths**
- **Pre-Defined Scripts of Leader Maneuvers**
- **Occasional Pedal Usage**



BOEING

Testing Summary

- **Flight Test**
 - Two Evaluation Pilots
 - One Flight of 5.5 Hours Duration
 - Very Few PIOs Noted
 - Formation Trail Task Higher Workload Than Boom Tracking
 - Potential for Structural Mode Excitation
- **Simulator**
 - Minimum of Three Evaluation Pilots
 - Motion Response
 - Valuable at High Speed Test Points
 - Of Neutral Value at Low Speed Test Points
 - Structural Modes Not Modeled

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GSCS Status

- **Very Early in Data Analysis Phase**
- **Complete Set of Flight Test Data**
- **Similar Results in Fighter Studies**
- **Variable Stability Capability of Test Vehicle**
 - **Respect Flight Safety**



General Ft. Vs. Sim. Results

- **Simulator Harder to Fly**
 - **Control of Separation Distance**
 - **Differing Piloting Techniques**
 - **Simulator Generally More PIO-Prone**
- **Level of Target Aggressiveness**
 - **More Aggressive Target Required in Flight**
- **Pilot Ratings**
 - **Inconsistent Pilot Rating Trends in Simulator**
 - **More Consistent Pilot Ratings in Flight**
- **Coupling Between Pitch and Roll Axes**
 - **Degraded Axis Led to Perceived Change in Off-Axis**
- **Low Speed Motion Cueing**



Discrepancy Factors

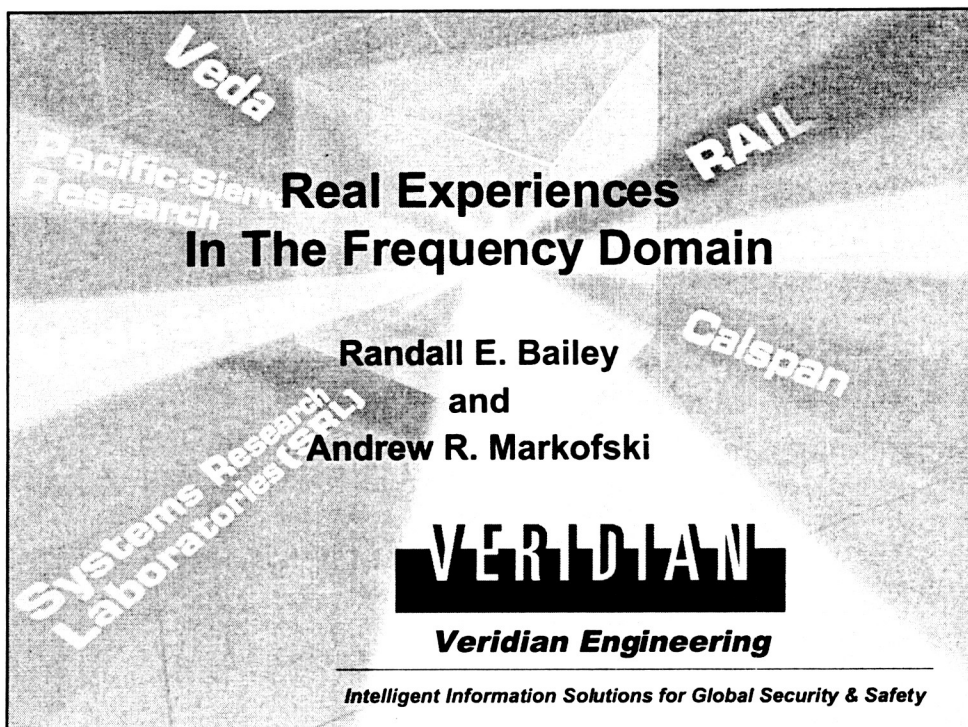
- **Simulator Transport Delays**
 - Visual, Displays of Sensor Information, Motion
- **Reduced Simulator Cueing Environment**
 - Level of Visual Detail
 - Depth Perception
 - Visual System Field-of-View
 - Visual System Alignment to Fuselage
 - Motion Responses
 - Travel Limitations
- **Differing Pilot Input Spectra**
 - Pilot Adapting to the Situation
 - Structural Mode Impact



GSCS Background

- **Sponsored By AFRL/USAF**
 - Technical Monitors: Wayne Thor & Dave Leggett
- **Flight Test Planning**
 - August 1996 - March 1997
- **Simulator Evaluation & Analysis**
 - April 1997 - August 1997
- **Flight Testing**
 - August 1998
- **Data Analysis**
 - Ongoing






Outline

“Real (and Imaginary) Experiences in the Frequency Domain”

- **Background**
 - Purpose of Briefing
- **Frequency Domain Analysis ‘Fundamentals’**
- **Real Data Analysis**
 - Realistic Assumptions?
- **Concluding Remarks**



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Flight Research Group


- Not intending to be too “Complex” with this presentation on frequency response analyses - therefore, the presentation title is only “Real Experiences in Frequency Domain” as opposed to “Real and Imaginary Experiences in Frequency Domain.” Pun intended.
- This is the outline of talk.
- What is meant by “Real Data” is experiences where the assumptions needed for frequency domain analysis are implicit -- unspoken, but may not be realistic or compatible with data from real airplanes.
- In many cases the ease of use of the tools themselves tempt an engineer to treat the analysis as a black box.

Frequency Domain

- **Purpose:**
 - **Enlighten Users (and Analysts) Into Practicalities of Frequency Domain Analyses**
- **Primary Issue:**
 - **Assumptions**
"Engineers Will Typically Assume Everything But the Responsibility"
 - **Anonymous Examples**



Flight Research Group SPEAK YOUR MIND!


Veridian Engineering

- So the purpose of this presentation is an attempt to enlighten the users and analysts involved in frequency domain based FQ/PIO criteria of the errors in their ways... To champion the cause of common sense over common practice.
- The problem is NOT necessarily the criteria or using the frequency domain - the problem is that the analyses for nonlinear/real aircraft data are not trivial nor are they "independent" of assumptions. The criteria are not explicitly considering these assumptions and the users are not aware of the assumptions.
- Engineers are infamous for "assuming" everything but the responsibility. Assumptions are always used. Keep knowledge of them and use engineering judgment for applying techniques wisely.
- Maybe not such a good idea to bash engineers in front of a roomful of engineers. Probably would have gone over better at SETP or at a board meeting. Hmm....
- Anonymous examples are used in this presentation to highlight "assumptions"
 - The examples are of using tools, applying these criteria and concepts rigidly. The definitions in many cases need revision and clarification. Assumptions may be incorporated in the criteria, or distributed to the user, or understood by the user/analyst. Wrong answers are being found.

Frequency Analysis Fundamentals

• **General Linear System**

$$r = A \sin \omega t \rightarrow \boxed{W(s)} \rightarrow y$$

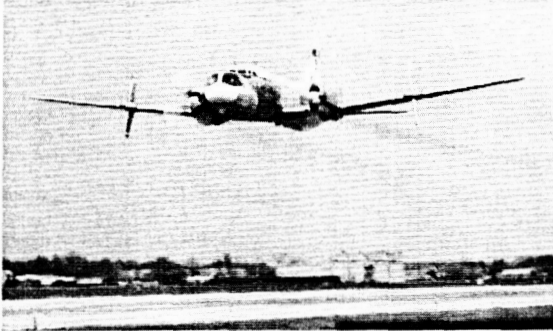
$$y(t) = AR(\omega) \sin[\omega t + \phi(\omega)]$$

• **Partial Fraction Expansion**

$$y(s) = \underbrace{\frac{R_{11}}{s + j\omega} + \frac{R_{21}}{s - j\omega}}_{\text{Particular Solution (Steady-State)}} + \underbrace{\text{other terms}}_{\text{Complementary Solution (Transient)}}$$

• **For Particular Solution:**

$$R(\omega) = |W(j\omega)|, \phi(\omega) = \arg W(j\omega)$$



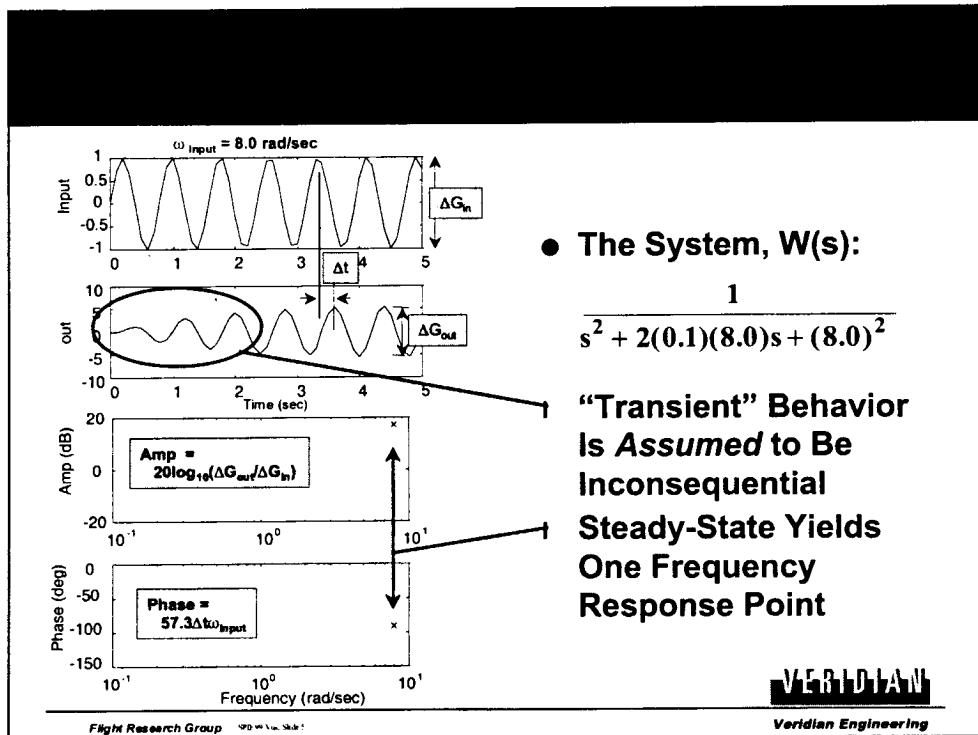
**The Frequency-Response Function
of a Linear System
Is Uniquely Determined By the
Time Response To Any Known Input**

Ref: Linear Control Systems, J.L. Meliss and Schuler, D.G.,
McGraw-Hill Book Company, New York, 1969

Flight Research Group NPD 99-1-100-100-1

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Veridian Engineering

- Emphasis on **FUNDamentals**... The fundamentals of freq. domain analysis are that the response ($y(t)$) out of an arbitrary system (W) in response to an input, r , can be decomposed by partial fraction expansion into essentially three terms using Laplacian operators.
- The first two terms are the “particular” solution. The remaining terms are the “complementary” solution.
- The “particular” solution is the “steady-state” contribution of the response, y . The time response, y , is thus described from the frequency response of black box (or transfer function) where R = magnitude and ϕ = phase of W .
- The key to this fundamental property and why Frequency domain analysis is so nice for engineering use, is that “The frequency response function of a *linear* system is *uniquely* determined by the time response to any known input.”
- The key principles/assumptions to remember from this are: “**LINEAR**” and “**Ignoring the Other Terms**”



● The System, $W(s)$:

$$\frac{1}{s^2 + 2(0.1)(8.0)s + (8.0)^2}$$

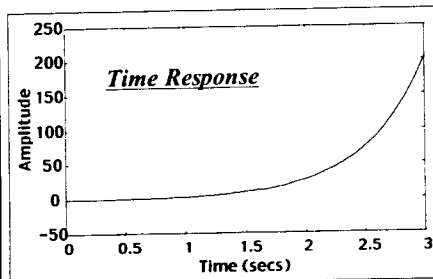
“Transient” Behavior
Is Assumed to Be
Inconsequential
Steady-State Yields
One Frequency
Response Point

- An example of these principles is shown.
- Transfer function of system, W , is as shown.
- Input is 8.0 rad/sec sine wave.
- After transient behavior (assumed to be inconsequential), steady-state can be used to find phase and gain (freq. response) at the input excitation frequency.
- The opposite principle also works (freq. domain to time domain) since we are analyzing a LINEAR SYSTEM.

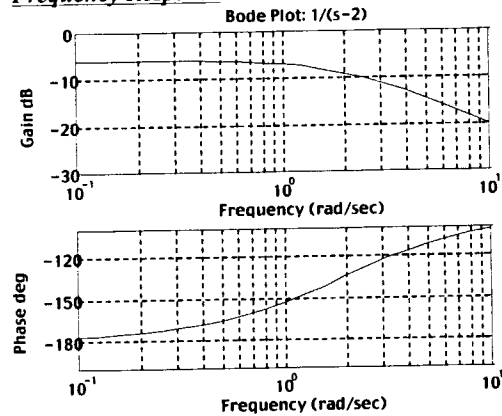
- **Transient Behavior Is Inconsequential**

- **When Is It Not?**

- Prime Aircraft Example: Unstable Systems



Frequency Response



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- THEORETICAL = do not apply to REAL WORLD

First example of a BAD ASSUMPTION.

- Ignoring “transient behavior”

For example, the best example of when this is a problem is for an unstable system.

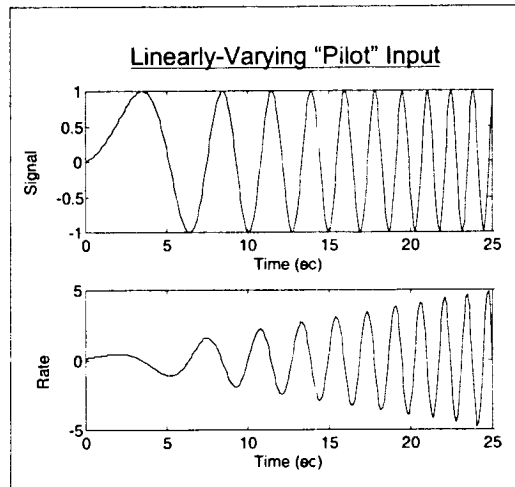
Unstable systems have frequency responses. The uniqueness properties between time and frequency domain still apply.

The problem is that it is **impractical** for this identification in the real-world. From the time response, the transient behavior “overwhelms” the time response and the “steady-state” frequency response characteristic is “hidden” in all practical sense of the word.

This point will be returned to at a later point in presentation.

● Why FFTs?

- **Extremely Efficient Algorithms for Computation of Spectral (Frequency) Characteristics**
 - Utilizing Power of 2 Significance in Fourier Transformation
- **Entire Frequency Response "Answers" from One Data Run**

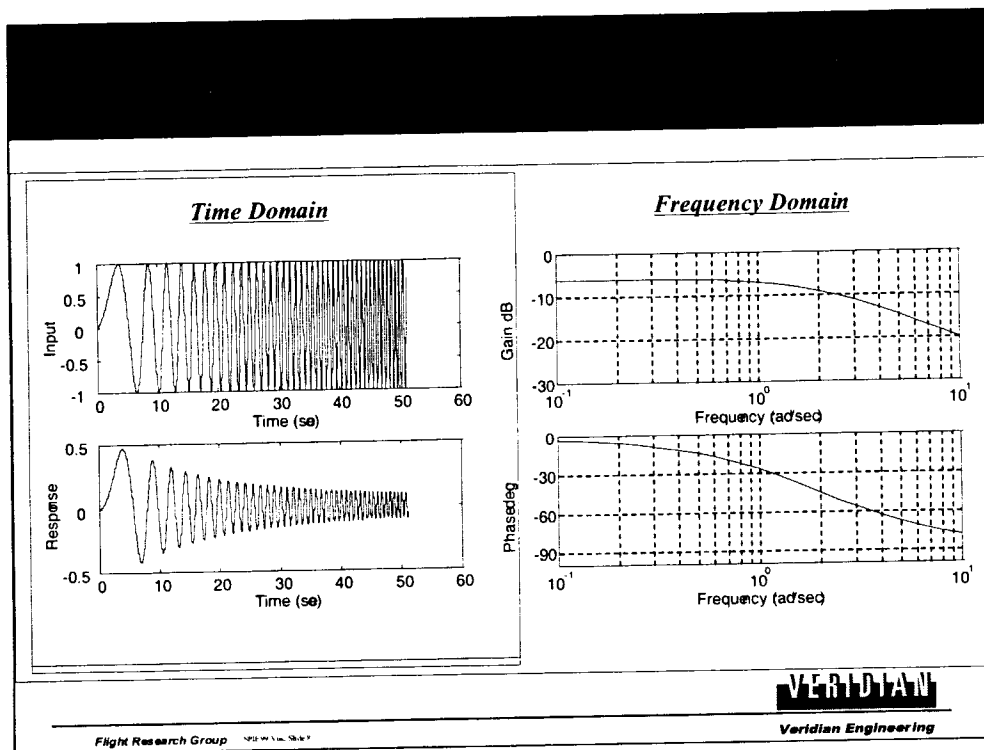


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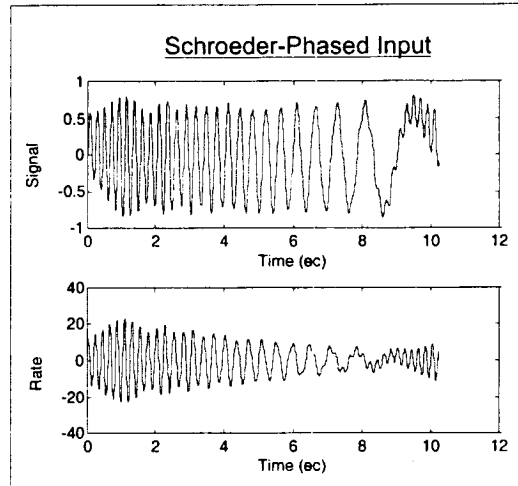
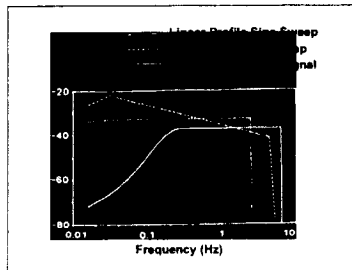
- Most practical method for frequency response computation occurs from Fast Fourier Transformations.
- Extremely efficient algorithm for transformation to frequency domain. Utilizes power of 2 in time history sample.
- "Entire" answers from one time history.
- Involve a whole set of their own ASSUMPTIONS



- Example of time response and frequency response.
- Example showing a “linearly varying” frequency input.
- Note that this is for a linear system.
- Everyone can do them. No pain, no suffering.
- Tools make it easy to apply FFT without looking at the whole picture.
- Of course, now that everyone can do them. Everyone does. Do they all know the “underlying assumptions” involved in this transformation?

- “Garbage In, Garbage Out”?
- “A Little Knowledge is a Dangerous Thing”?

- “Optimal” Input “Shape” for FFT Computation?
- Broadband Input?



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Flight Research Group NPS 99-100-0000

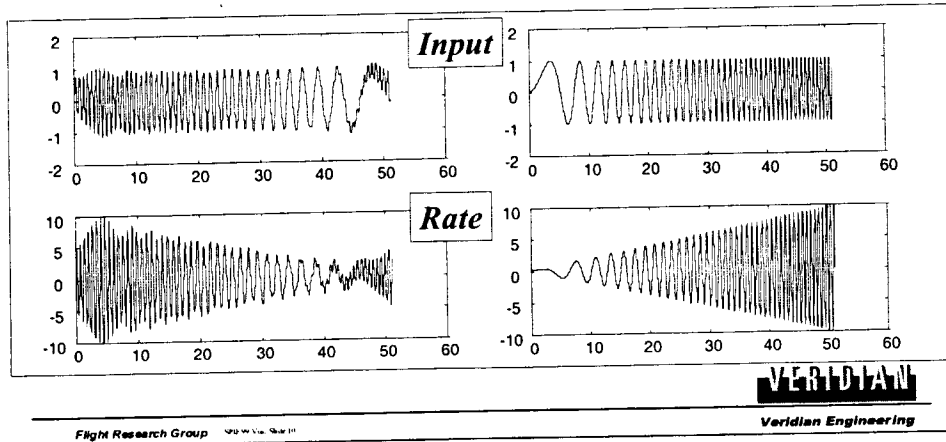
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- A practical matter, not considered by many, is the importance of the input excitation.
- Unlike the “frequency sweep” input, it is not the “optimal/ideal” input
- Schroeder-phased inputs are better. Chirp-z inputs are also better.
- We will visit the importance of input on the next chart.

● All (Freq. Sweep) Inputs Are As Good As Any Other

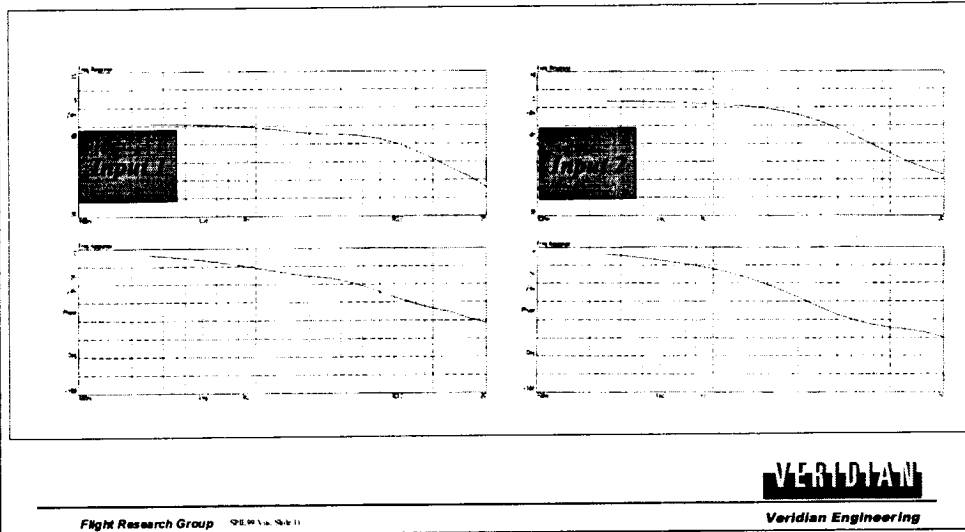
■ Considerations:

Input Amplitude / Input Rate / Frequency Content /
Analysis Technique / Flt Condition

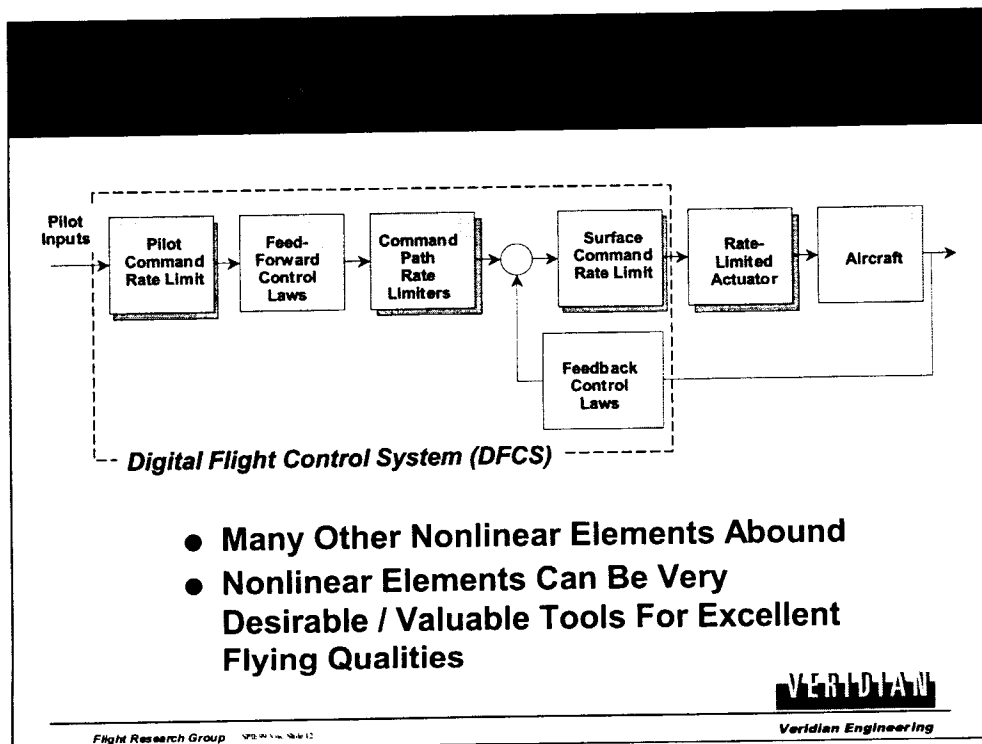


- Another bad assumption illustrated concerning inputs.
- In practical terms, the input for the frequency sweep has to consider: the amplitude, amplitude rate, frequency content, analysis technique that will be used, and flight condition.
- Again, for Single-input, single-output, no noise, linear, time-invariant system analysis, all of these items are immaterial (with exception of frequency content). This is NOT the real-world.
 - Input amplitude: important for signal-to-noise ratio.
 - Input rate: important for “rate-limiting effects”
 - Freq. content - determines range of “valid” data
 - Analysis technique - ensembling of windowed data usually requires “broadband” / noise-type excitation across entire time history. Schroeder-phased inputs are tuned to frequency FFT harmonic frequencies (for lack of a better word).
- MORE DATA = Better??? Only for certain circumstances
- Flight Condition - Tradeoff between “constant” flight condition and accurate low frequency identification. Phugoid issues in particular. Low frequency inputs will excite phugoid (i.e., speed changes) - these are “real” effects yet can be “different” than what some people want (i.e., constant speed approx. for instance). Have to be careful what you asked for...

• Input 1 and Input 2 Differ Only In Magnitude



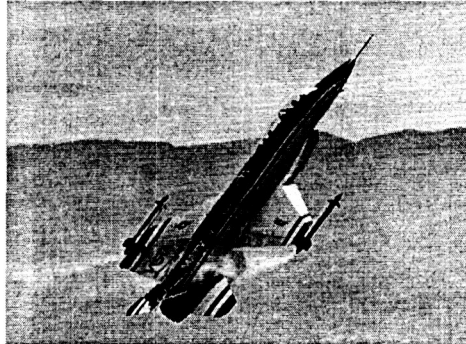
- An example of input importance.
- System under identification is identical.
- Comparison of two frequency responses generated using two different sized inputs.
- Very, very different results depending upon input size.
- System was nonlinear.
- Analyst said - "what's going on. You asked for frequency responses and I got different "answers" every time."



- A schematic diagram of “typical” rate limiter locations. Many other “nonlinearities” abound - not shown.
- Some limiters are intentional and necessary (ie., the surface command limiter) - others are physical limitations (i.e., the actuator)- some are used “erroneously” (such as the pilot command rate limiter) because HQDT “requires” it. (For instance, if max. value, unrealistic inputs are used just for “PIO” evaluation, an easy solution for the designer is to slap a “pilot command rate limiter” in the forward path. The result is that a “PIO” will not happen for the unrealistic HQDT task. However, the real result is that 20-25 msec of time delay is now added to the flight control system and the potential for a real PIO is increased just because some people teach the wrong thing for HQDT.)
- Nonlinearities are not bad. In fact, they are quite the opposite. They are necessary for good FQ. The only problem is making sure that the FQ tools can identify these “good” qualities and not legislate against them.

This is not an LTI system

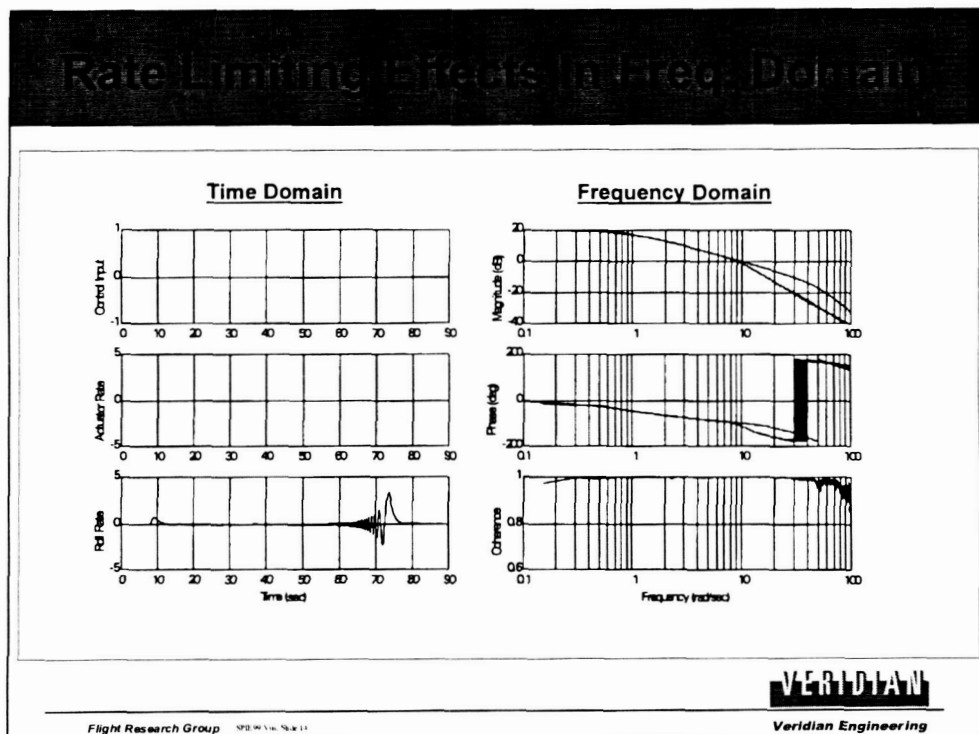
- **Issues in Frequency Response Derivation:**
 - Single-Input, Single-Output
 - Linearity
 - Time-Invariance
 - Stationarity
- **Unstated Assumption:**
Linear Time-Invariance (LTI)



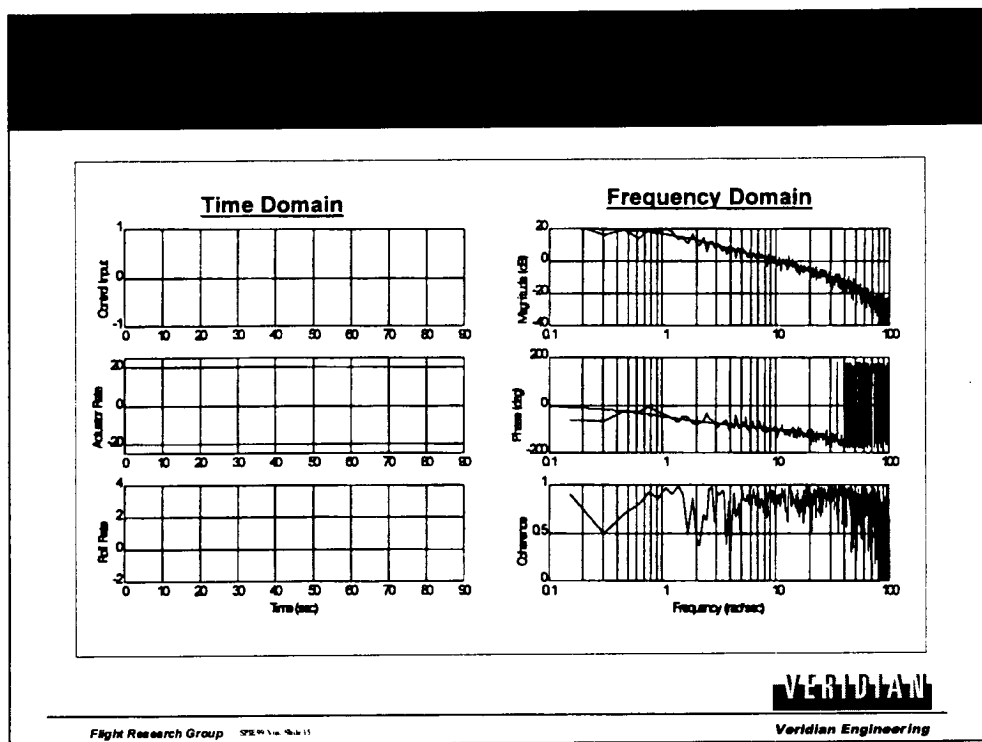
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- THEORETICAL basis = do not apply to REAL WORLD
- The assumptions in freq. response derivations are:
- (Many times, but not necessarily) Single-input, single-output (I.e., output is caused only by the one input)
- (Always) Linearity (ie., linear system is $q = M_{\alpha}\alpha + \dots$, nonlinear system is $q = M_{\alpha 2}\alpha^2$ etc.)
- (Always) Time-invariance (ie., y = function of time) (Stationarity is the “controls engineers” term for time invariance)
- Linearity conditions are easily violated by changes in flight condition, position and rate limits, breakout force, friction, hysteresis, nonlinear command gradients, etc...
- Time variation is also a rate limiting effect. In other words, the FFT analysis is assuming that over the time period for the identification, that the system has not changed.



- Can rate limiting affects be identified in Freq. Domain? Yes. Here's an example.
- Note phase rolloff and amplitude attenuation.
- However, the most important condition for this result is that the rate limiter is no longer "time varying" - it's a quasi-steady. See rate signal above.
- HOWEVER, hard part - for this to occur, amplitude and frequency of the input to the rate limiter element depend on lots and lots of factors *in real situations that cannot* typically be predicted or repeatable from run-to-run, pilot-to-pilot, etc.
- Particularly for rate limiters that are "buried" in a control law - that is, the inputs depend not only on the pilot inputs but also on the feedbacks, etc. A prime example is the actuator command rate limiter shown on a previous slide.



- Here's a more "typical" example. Note variation in rate limit. Also, noise is added to input and output. (Not a laboratory condition!!)

- Introduce "coherence function" at this point.

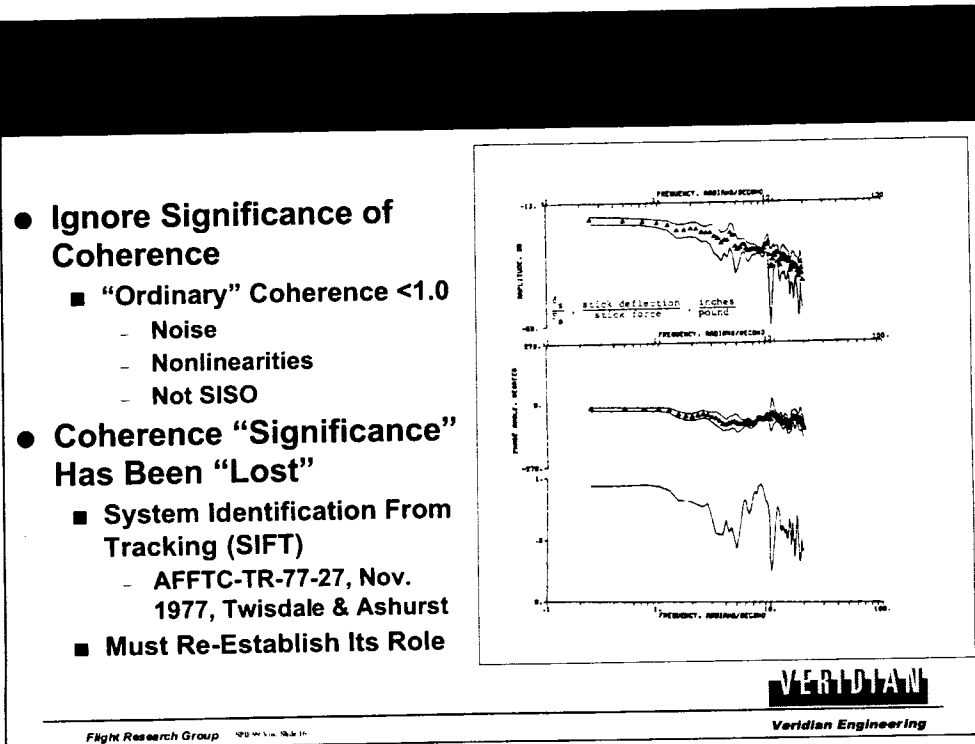
Purpose: Evaluation of "goodness" of FFT.

Real name: "Ordinary" coherence function for SISO case.

- Coherence lets analyst know if FFT/freq. resp. is "valid"

- Not valid (ie., coherence values go < 1) if:

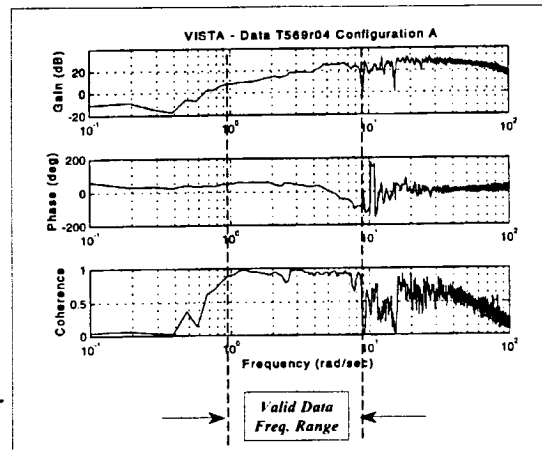
- 1) Extraneous **NOISE** is present in the measurements
- 2) System relating x and y (input and output) are not linear
- 3) Output is due to input as well as other inputs -- not SISO



- Reiterate: Ordinary Coherence < 1 - Noise, Nonlinearity, Not Single-Input, Single Output (i.e., multiple inputs, turbulence, etc can cause violation of SISO)
- Can't just "ignore" coherence - have to understand why coherence does equal 1.0. Involves more analysis of the input and output, and tracking the error.
- Coherence has been used as a "discrete" i.e., if coherence > 0.6 data is "good" Not a good thing to do unless you make that level very stringent (coh > 0.9 , > 0.95). Can be dangerous (Bad Assumption). Coherence is similar to correlation coefficient analogy. 1.0 correlation is "perfect." Correlation = 0.6, correlation to real data is *not* good. Many examples of coherence > 0.6 , < 0.9 where data was "bad." (i.e., not what was expected. If left un-investigated, would have gotten wrong answer)
- More appropriately, coherence is *directly* relatable to error in frequency response estimate. This significance has been lost! (Twisdale did this 20 years ago!)
- Must get back to its significance if frequency response analysis is going to do anything for us.
- Answers from criteria using this data will tend to be regions rather than points

- **Following
“Established” Rules**

- **Equivalent Systems:**
Typical Range for Match:
0.1 to 10-20 rad/sec
 - Ignoring Coherence,
or
 - Using All Data Points,
Thus, Distorting
Weighting Functions,
or
 - Identification /
Inclusion of Low and/or
High Frequency LOS
Terms Beyond “Valid”
Data

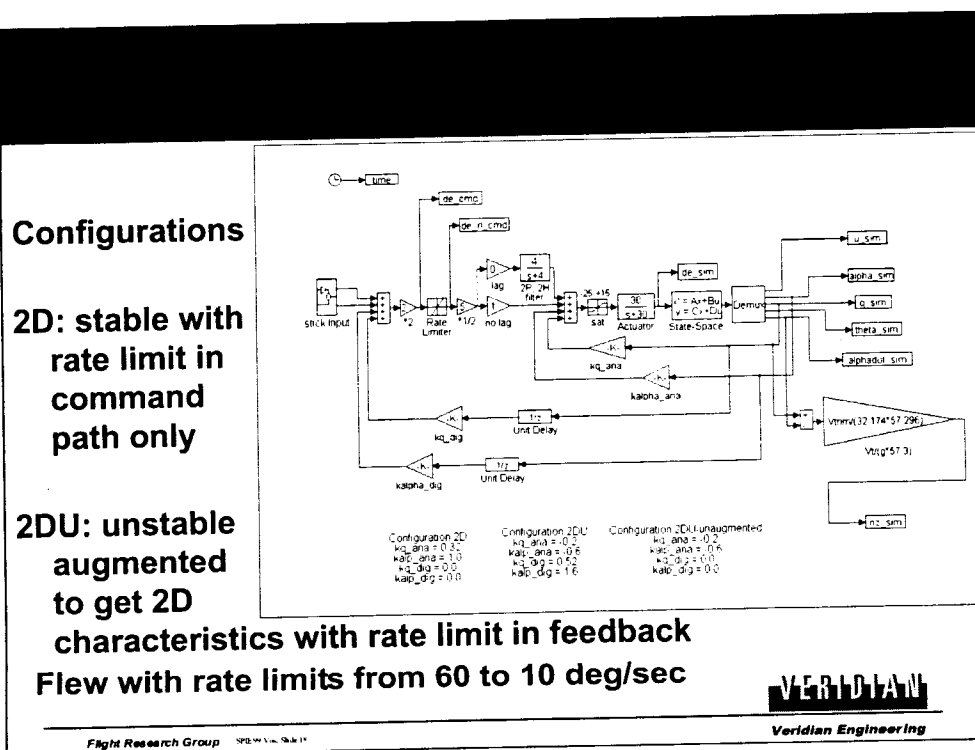


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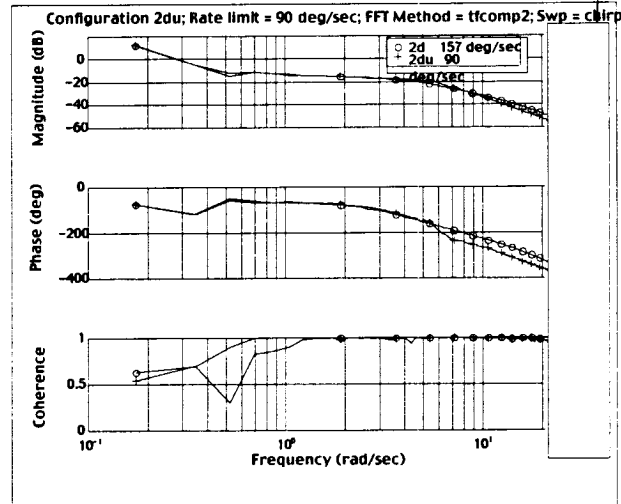
- We’ve had experience where - after “derivation” of a frequency response, the “rules” are blindly followed for such things as an equivalent system.
- Neglects phugoid, high order & nonlinear dynamics, structural dynamics, sensor dynamics, and recording filters. Assumes constant flight conditions.
- Coherence has been ignored (see previous slide)
- Persons have used “all the data points” from a FFT for equivalent system derivation. This inappropriately weights the high frequency equivalent systems match at the expense of the low frequency due to the $1/dt$ frequency spacing of the data (more pts at high freq., fewer at low freq.)
- Although the freq. range of valid data was “narrow,” extrapolation outside the range was allowed to get a “equivalent match.” Unfortunately, answers can be MISLEADING.



- This is a Simulink diagram used for the “Have Limits” flight test program.
- This model was used to assist the engineers in visualizing the set-up of the experiment.
- Subsequent to the experiment, this model has been distributed to users to aid in analyzing the “Have Limits” data.
- Key “feature” in the data base, analysis, and set-up for the “Have Limits” flight test is Configurations 2D and 2DU.
- Config 2D has the rate limiter in the forward path only.
- Config 2DU was a simulated unstable airframe - using analog feedbacks, without rate limiting around the NT-33 Airframe - with an outer loop feedback structure to augment the simulated unstable airframe to match Config 2D dynamics. The key difference is that the rate limiting term includes the feedbacks for Config 2DU and an unstable airframe.

Problem With 2DU is Instability

- Rate Limiting Caused "Lock-Out" of Control
- With 60 deg/sec Rate Limit CHR: Two 10's
- Same Rate Limit in Forward Path Showed No Noticable FQ Degradation



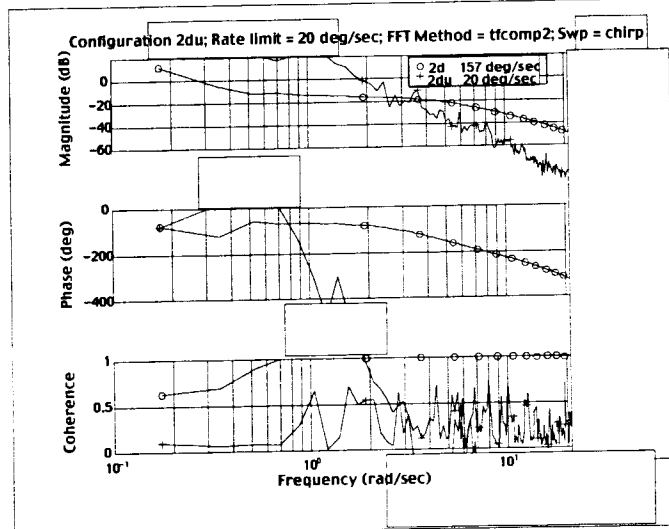
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Flight Research Group 07/20/11 10:44:14

- In a very brief summary, a key conclusion from the Have Limits program is that Config 2DU have very poor flying qualities. Pilot Ratings were 10 for the least amount of finite rate limiting (ie., with 157 deg/sec rate limiting - essentially no rate limiting, 2DU got ratings of 2, 5, and 4. But for as little as 60 deg/sec rate limiting, two 10's were given.
- The FQ deficiency for Config 2DU was loss-of-control. Once the aircraft was on the rate limit, the feedbacks were locked-out and the aircraft entered a departure scenario. (NT-33 VSS was disengaged upon loss-of-control).
- Same rate limit, in forward path, was not a noticeable flying qualities influence.
- Using the Simulink model and assuming a pilot input size, "rate limiting" effect in frequency domain is noted.
- Issues:
 - 1 - have to "assume" a pilot input size;
 - 2 - can't get freq. domain "answers" for rate limit values < 90 deg/sec
Only done analytically, not flown.

With Control Lock-out Due to Rate Limiting

- Incoherence
Time-Varying
System
- Identification
of Unstable
Aircraft
Without
Stabilization

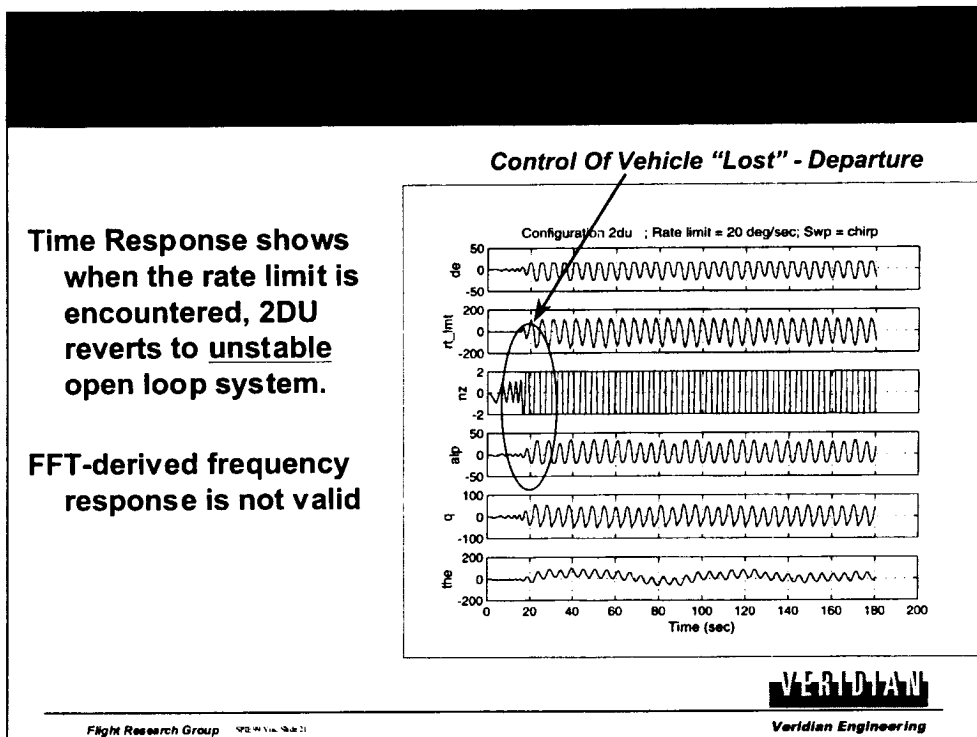


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- As example, for 20 deg/sec rate limit, the frequency response data for 2DU is garbage. Reason: the aircraft hits a loss-of-control issue. Time varying system with nonlinearity. Also, once aircraft is in rate limiting, the feedback is “ignored” and the bare airframe characteristics are what is being identified.
- The results are essentially not valid.



- Here the time history really shows what's going on. Specifically, like the earlier example, the transient response is NOT negligible.
- Once aircraft is in rate limiting, the feedback is "ignored" and the simulated unstable bare airframe characteristics are driving the response
- Once the rate limiting starts with Config 2DU loss-of-control occurs. Note the time histories where alpha goes +/- 25 degrees and the g's go way beyond +/- 2 g's. (The plot is artificially limited to +/- 2 g's)
- FFT-derived frequency response is not valid since it is no longer linear aerodynamics or time invariant.
- In fact the response immediately goes beyond the scope of the small perturbation model.
- These agree with the results experienced in the flight experiment.

CONCLUDING REMARKS (1)



- **Frequency Response Derivations**
 - Extremely Valuable Information
 - Most 'Common-Knowledge' Properties *Only* Pertain to Linear System Analysis
 - Caution / Care Must Be Used In Real Situations *Particularly* Nonlinear, Time-Varying Systems Analysis
 - *i.e., Today's Aircraft!!*


Flight Research Group SPE-96-116-88-12

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- Said enough. Just summarizing the points...
- Don't let them kill the messenger, Andy.
- Reiterate that Freq. Domain analysis *IS* a powerful tool - very useful. However, it can't be used carelessly. Unfortunately, it is...
- I've cited some examples. Many, many more were available but I couldn't put them into a 30 min. presentation.

Tools & Techniques for Proper Analysis Are Available

- Tools & Techniques for Proper Analysis Are Available
 - e.g., System Identification From Tracking (SIFT)
- Retain Engineering Judgment in Analyses
- Scrutinize Assumptions
- Develop 'Standards'



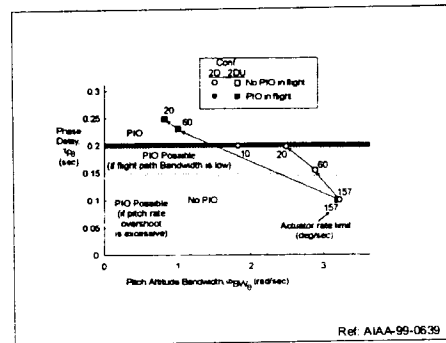
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Flight Research Group NPS 99-100-100-21

- Reiterate that tools are available or can be developed. Not rocket science.
- Clearly, evidence abounds that the fundamentals of frequency domain analysis are being ignored, forgotten, whatever - but things will get worse if they don't stop, step back, and think about what is being proposed and done.
- Standards for analysis will help.

- **AIAA-99-0639**
**“Determining
Bandwidth in the
Presence of
Nonlinearities”**

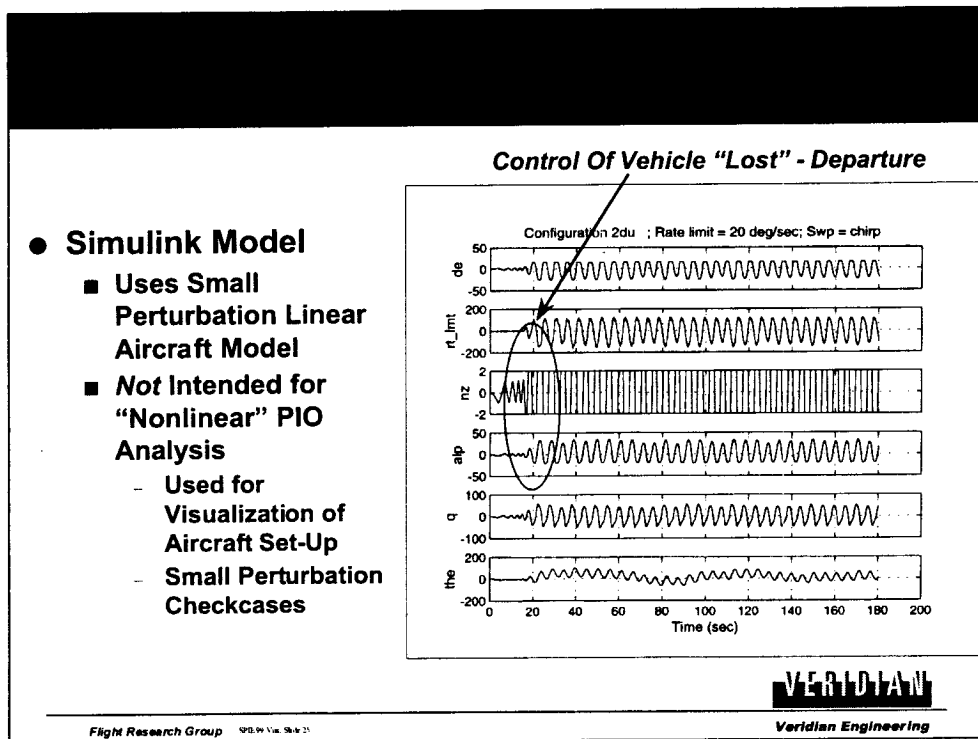
- ### ■ Correctly Predicts Pilot Rating for Wrong Reason?

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Flight Research Group 1970-99 Vol. 5, Slide 21

Veridian Engineering

- In AIAA paper 99-0639, frequency domain data was presented for these cases.
- Don't know how these data were generated - can't repeat analysis.
- Further, they should show unstable aircraft behavior. They don't
- Finally, the frequency responses in 99-0639, show a feedforward, time delay effect of rate limiting - not the loss-of-control issue. That's what the bandwidth criteria, shown on the plot, indicate.
- Basically the criteria are predicting the right answer for the pilot rating, but for the wrong reason. The real data - the pilot comments - don't match the criteria. The criteria doesn't say "loss-of-control" for this configuration.



- Another problem with these analyses is the use of the Simulink model.
- The model was intended for visualization by Calspan and AFTPS engineers of the experiment. It was also used for small perturbation checkcases.
- The model uses a simple three degree-of-freedom, small perturbation math model of the NT-33.
- The scope of the validity of this model has NOT been determined. However, clearly, it is not valid once the rate limiting occurs with Config 2DU and loss-of-control occurs. Not the time histories where alpha goes +/- 25 degrees and the g's go way beyond +/- 2 g's. (The plot is artificially limited to +/- 2 g's)
- Again, the model was never intended for the purposes that it may be being used for at this time. This should have been obvious from inspection of the "aircraft" model form.

Pilot Modeling for Resolving Opinion Rating Discrepancies

David B. Doman
Air Force Research Laboratory
April 8, 1999

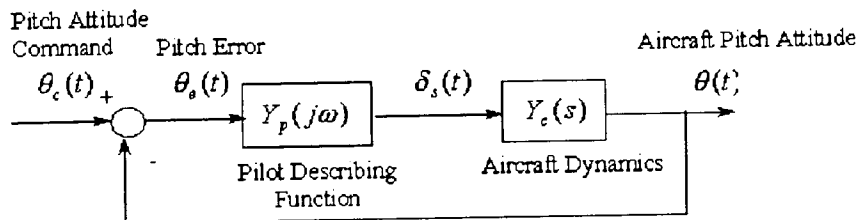


Background

- Inter/Intra pilot opinion rating variability has confounded flying qualities engineers since the inception of the rating scales
- A method for extracting quantitative information from experimental data to provide insight into rating variability and help gauge the validity of ratings would result in a valuable engineering tool.
- **Idea #1** Extract metrics developed for pilot-in-the-loop flying qualities criteria from experimental frequency response data.
- **Idea #2** Estimate a range of ratings by using highly accurate models of pilots and varying physiological parameters over a reasonable set of values.



Pilot-in-the-Loop Pitch Tracking



Performance - Workload Criteria

Neal-Smith, Bacon-Schmidt, Efremov MAI:

- Closed-loop resonance
- Pilot phase compensation, (Pilot phase excluding neuromotor lag and time delay)
- Each assumed all pilots behave the same

Neuromotor lag (related to aggressiveness) and time delay vary over pilot population, What range of pilot ratings can be expected?



Optimal Control Pilot Models

Assumptions

- Compensatory Tracking (SOS)
- Minimize mean squared frequency weighted tracking error subject to human operator limitations

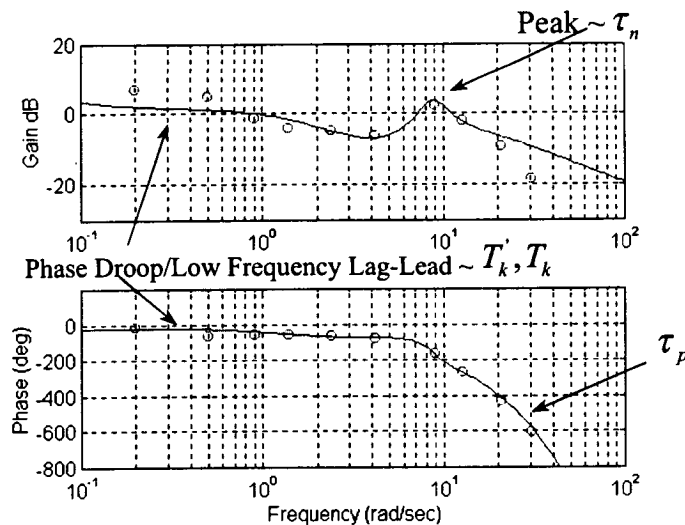
$$J = E_{\infty} (e_f^2 + f \dot{u}_p^2)$$

$$e_f(s) = \frac{T_k' s + 1}{T_k s + 1} e(s)$$

Control rate weighting f directly linked to pilot's neuromotor dynamics.

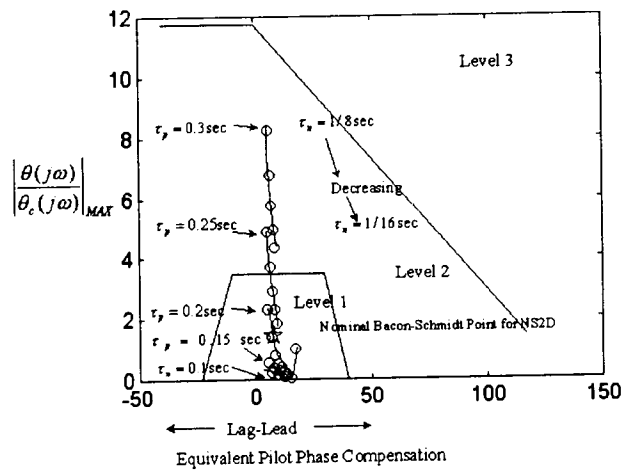


Fitting Describing Function Data Using Modified OCM

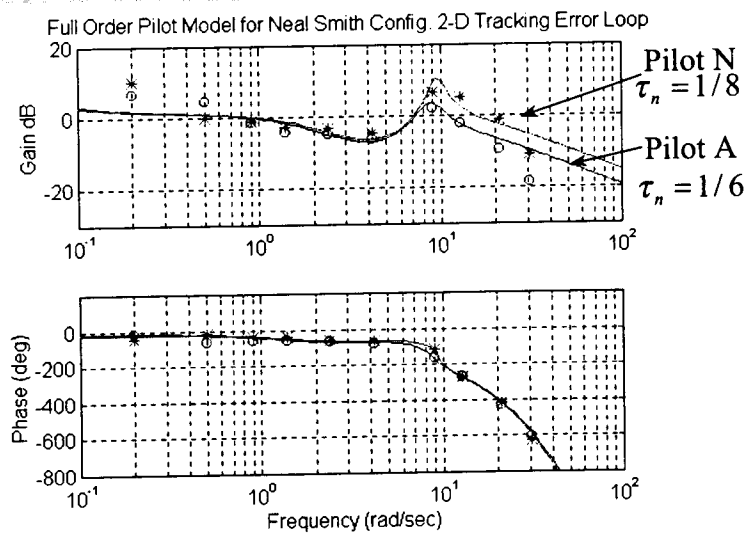




Bacon-Schmidt and NS-2D

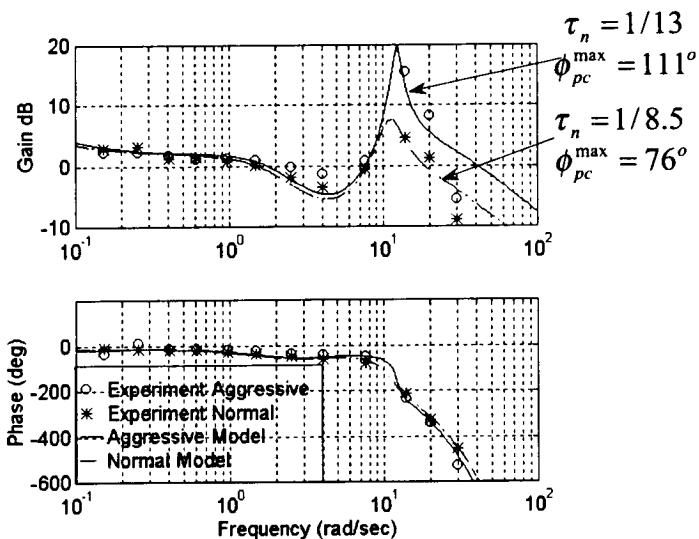


Evaluation of NS-2D (USAF/LAMARS)





Aggressive vs. Normal Behavior, Single Pilot (PC Simulation)



Conclusions


- OCM methods have the potential to describe differences in and among pilots in closed loop compensatory tracking tasks for linear controlled elements.
- High frequency roll-off characteristics of the human appear to be higher than 1st order as predicted by OCM.
- Performance and workload metrics extracted from OCM fits to experimental data could provide insight into rating variability and possibly help gauge the validity of ratings.
- Use as a predictive tool to estimate the range of ratings that could be expected from a pilot population by varying time delays and neuromotor lag time constants over a reasonable range.

Mary Shaffer:



- Acknowledgements
- Closing remark

I'd like to thank...



- | | |
|--------------------|-------------------|
| • Paul Steinmetz | • Dave Mitchell |
| • Frank Newton | • Moderators |
| • Everlyn Cruciani | • Presenters |
| • Patti Pearson | • Attendees |
| • Dennis Calaba | • Tour organizers |
| • Darlene Homiak | • Ed Schneider |

In closing:



- “All happy families are alike, but each unhappy family is unhappy in its own way.”
Leo Tolstoy, *Anna Karanina*.
- “All good aircraft are alike, but each bad aircraft is bad in its own way.” Mary Shafer

Appendix 1

Pilot-Induced Oscillation Research: The Status at the End of the Century

**NASA Dryden Flight Research Center
Edwards, CA
6-8 April 1999**

For well over a century, as long as people have been gliding and flying, aviation safety has been threatened by pilot-induced oscillations (PIOs). As our calendars prepare us for 2000, the time for reviewing the status of PIO research is at hand. NASA Dryden Flight Research Center is pleased to sponsor an open workshop doing just this in a three-day session on 6-8 April 1999.

The last public presentation of PIO research was in 1995 and since then, a number of major PIO research programs have been completed. The results of these programs will be presented at this workshop, as will be the results of other studies, hypotheses, and proposals for further research.

The only restriction is that discussion be limited to safety-related PIO; possible topics include criteria, simulation and flight testing, the pilot's role, design considerations, recent experiences, rate limiting effects and minimization techniques, civil certification, military acceptance testing, analytic techniques, and more. In no way is this the entire list of possible topics and your participation, discussing any topic you feel is relevant, is solicited. It may be that the coffee-break talk alone can offer some insight into a difficult problem you have.

As this is a workshop, with short notice, the expectation is that presentations will not be as formal as conference papers. Copies of the presented material, with whatever supporting material the presenter offers, will be produced. If possible, the entire workshop will be videotaped and copies will be available.

This workshop will be unclassified and open to anyone interested, regardless of affiliation or citizenship. There is no fee for attending. For planning purposes, however, an estimated attendance is required; the response form indicates a variety of methods for responding, however tentatively. Requests to attend must be received by 19 March.

Presentations must be proposed by 5 March. Presentation requirements, as indicated on the response form, must be received by 19 March. Dryden can support viewgraphs, 35mm slides, videotape, and PowerPoint projection (other software requires providing PC-based software). Advance submission of presentation material and supporting material will aid the production of copies for attendees before the end of the workshop. Presentations are nominally scheduled to last 30 minutes, with 10 minutes for questions. Should this be insufficient, please explain the need for more time on the response form.

Please circulate this announcement to anyone you think will be interested. Anyone interested in handling qualities, PIO, aviation safety, pilot-vehicle interfaces, and related topics should be informed of this workshop, as other forums for discussing such topics are no longer common.

**Please respond quickly if you think you might attend,
particularly if you are considering making a presentation**

**Pilot-Induced Oscillation Research:
The Status at the End of the Century**

**NASA Dryden Flight Research Center
Edwards, CA
6-8 April 1999**

Attendance (Reply by 19 March, please):

Your full name: _____

Name you want to be called by, for badge _____

Affiliation _____

Address for further _____

mailings about _____

the workshop _____

Telephone _____ Fax number _____

E-Mail address _____

Preferred method for further contact: ☐ Mail ☐ E-Mail ☐ Fax ☐ Telephone

Presentation (Reply by 5 March, please):

Title _____

Co-Authors _____

Presentation media: ☐ Viewgraph ☐ 35mm slides ☐ Videotape
☐ PowerPoint ☐ Other software ☐ Other medium

Special requirements _____

Send this form, as soon as possible, to:
NASA Dryden Flight Research Center
Ms Mary Shafer
Mailstop 4840D
P.O. Box 273
Edwards, CA 93523-0273
(805) 258-3396 (workshop only) or (805) 258-3735 (regular number)
(805) 258-2586 (Fax) or email to Mary.Shafer@dfrc.nasa.gov

Pilot-Induced Oscillation Research: The Status at the End of the Century

**NASA Dryden Flight Research Center
Edwards, CA
6-8 April 1999**

Presentations Information:

All speakers who prepared their presentations with PowerPoint are *implored* to bring a copy on disk, plus a duplicate disk, for direct projection. We will have the projector and a computer with the software and would greatly prefer to project the computer version rather than resort to using transparencies. We find that the projected computer image is superior to the projected viewgraph. Speakers who used other software can also project directly if they can bring a laptop or a version of the software that allows reading the images, although such speakers would be wise to bring viewgraphs as a backup on the off chance that this won't work. E-mail me if you didn't use Word or PowerPoint and we'll see what we can do.

Speakers who are using the projection system are asked to bring a paper copy for adding to the handouts; if color is important to understanding the viewgraph, I can make a limited number of color copies, I think.

Any speakers who want more than 30 minutes for their presentations should let me know immediately. More time is available, but I can't allocate it unless I know who needs it.

The preliminary schedule has, as is inevitable, changed, but most of the changes are to the order of presentations within session. Speakers whose presentations have been moved to other sessions have been consulted before the move was made. I'll send out a revised copy by Friday.

SR-71 Tour:

I'm still working on getting permission to have the SR-71 tour. If it is granted, the tour will be during the second half of the time set for lunch on either Wednesday or Thursday and the schedule adjusted accordingly on the other day. For those not familiar with hangar visits, there are just a few obvious rules.

1. Stay 15 ft (5 m) back from the aircraft unless the crew chief gives permission to come closer.
2. Don't touch the airplane without permission
3. Photos are allowed, but flash bulbs (not built-in flashes, but the actual bulbs) are not allowed
4. If we are allowed to look at the cockpit, secure all loose items in shirt and jacket pockets, so that they don't fall into the cockpit and FOD it.
5. Watch your step, as there are cables and hoses on the hangar floor.

Getting Here

For those flying into the Los Angeles area, it will be necessary to drive to Lancaster (where the hotels are) and to Edwards. There are a number of airports in the area but Los Angeles International (LAX) is the most likely destination, although those who can fly into Burbank will find the drive shorter and easier. If you're arriving at LAX, you will take Century Blvd to the San Diego freeway, the 405, and get on it going north (Sacramento is likely to be mentioned) by going under the freeway and then right onto the on-ramp. Go north until the 405 merges with the Golden State freeway, the 5, and keep going north (this is the easy and obvious thing to do). A few miles beyond that take the Antelope Valley freeway, Hwy 14, north. This splits off the 5 on the right side and the city name is Lancaster. Stay on Hwy 14 until you get to Lancaster and then follow the instructions below if you're going to your hotel.

If you're arriving at Burbank, turn left out of the airport and go to the Hollywood Freeway, about two miles. Get on it going north and when you reach the 5, get on it going north. Keep going until you get to Hwy 14 and then proceed as described above.

To get to Dryden, take Hwy 14 north to Rosamond and exit at Rosamond Blvd, going east, to the right. Stay on Rosamond Blvd. In about 10 mi, you'll come to the Edwards AFB guard post, where you must show identification. Those of you with DOD or NASA ID will be waved in when you show it to the guard. Those with other forms of ID should do as directed by the guards. Pre-registered attendees will be on a list for admission. If there's any difficulty, tell the Air Force guard that you're attending the NASA PIO Workshop; if there's any further difficulty, ask the guard to call 258-3273

Dryden is about 10 mi beyond the guard post; stay on Rosamond Blvd though Main Base. The road will narrow to two lanes (from four) and you may think you've gone too far. About a mile after the road narrows, you'll see a number of metal bleachers on the left. The road to Dryden is on the right, just beyond these. There are signs, of course, and you can see Dryden down on the lakeshore. Turn right, cross the railroad tracks, and turn right at the second opportunity, just before the HL-10 lifting body on a plinth. Turn left into the parking lot right after you go by the F-104G, X-29, and two F8s. Walk to Visitor Registration, just across the street from the X-15 mockup, and go to the workshop registration desk.

Amenities:

The room we're meeting in is adjacent to the cafeteria. It is open for breakfast and lunch and also for breaks. The afternoon breaks will begin before the cafeteria closes at 1400.

The Dryden Museum and Gift Shop is in the same building and is open to the public. The Gift Shop sells film in addition to a variety of aviation and space-related souvenirs, including tee shirts, models, toys, pins, photos, and similar goods. They now take credit cards.

The Dryden Exchange, inside the facility, sells stamps and common over-the-counter remedies and toiletries (the cafeteria sells some remedies, too); access is easily arranged. The Dryden credit union can handle minor financial transactions, such as cashing traveler's checks (in US dollars); again, access can be arranged.

Dryden has public tours twice a workday; anyone willing to miss a portion of a session can go on the tour if there's enough space. Additionally, AFFTC runs a tour of Edwards on Friday morning, so anyone with an extra day can do the AFFTC tour on Friday morning and the Dryden tour on Friday afternoon. Let me know if you want to do this, as reservations are required.

Lodging:

The better hotels are in Lancaster, which is 35 mi (and about 45 minutes, counting parking) from Dryden. This list is just a few of them, mostly with restaurants and all the usual facilities. Members of the AAA can find a more complete list in the guidebook for California.

Desert Inn

44219 Sierra Hwy,

Lancaster

661 942-8401

661 942-8950 fax

mkt@desert-inn.com

Government rate \$60 + tax, corporate rate \$62 + tax

Leave 14 at Ave K, turning right (east), go a little over a mile to Sierra Highway (just before the railroad tracks) and turn left. The Desert Inn is a little more than half a mile, on the left.

Antelope Valley Inn

44055 Sierra Hwy

Lancaster

661 948-4651 (800 528-1234 for Best Western reservations in US)

661 948-4651 fax

Government rate \$63 (includes breakfast & 2 bar drinks every day), corporate rate \$63 + tax

Leave 14 at Ave K, turning right (east), go a little over a mile to Sierra Highway (just before the railroad tracks) and turn left. The Antelope Valley Inn is about half a mile, on the left.

Inn of Lancaster

44131 Sierra Hwy

Lancaster

661 945-8771

661 948-3355 fax

Government & corporate rate \$58.85 (includes breakfast every day, dinner Tuesday and Wednesday)

Leave 14 at Ave K, turning right (east), go a little over a mile to Sierra Highway (just before the railroad tracks) and turn left. The Inn of Lancaster is about half a mile, on the left.

Oxford Inn

1651 West Avenue K

Lancaster

661 522-3050 (800 522-3050 for reservations in US)

661 949-0896 Fax

Government & corporate rate \$55 + tax (Continental breakfast and happy hour included)

Marie Callender's Restaurant on premises

Leave 14 at Ave K, turning left (west), going under freeway. The Oxford Inn is on the right, quite close.

The Essex House

44916 10th St. West

Lancaster

661 948-0961

661 945-3821

essexhouse@hughes.net

Government & corporate rate \$62 standard room, \$74 king, \$78 suite (Buffet breakfast weekdays, continental breakfast weekends)

Leave 14 at Ave I, turning right (east) and go a little over a mile to 10th Street West, turning right. The Essex House is about 0.25 mi, on the left.

One loose end to tack down and some information on the local climate for people not familiar with the Southern California High Desert.

For larger PowerPoint presentations that won't fit on a diskette, there are two other options, CD-ROM or Zip. The laptop we'll be using for projecting has both a Zip drive and a CD-ROM (DVD, actually) drive.

Weather and what to wear:

Dryden is an informal place and I suggest that attendees adapt to the local standards. Business/government casual, which for engineers starts here at jeans and tee shirts and goes on to a point just short of dress shirts and ties (and for pilots starts and stops at flight suits), is suggested. I'm sure everyone will reach a proper balance of comfort, casualness, and appropriateness. As it is Spring here, a layered approach is often wisest.

The average high temperature for the week of the workshop is 70 degF (21 degC, if I've done the conversion correctly) and the average low is 42 deg F (5.6 degC). The average precipitation for the entire month of April is 0.01 in. (0.3 mm), so we're unlikely to have more than a trace of rain. I personally expect clear blue skies for the entire workshop. However, there is a fair chance of some wind, in which case the highs will be lower and the lows will be higher and, more to the point, the so-called wind chill factor will make it seem even colder. Right now, on Wednesday, 31 March, we've got a cut-off low in the area and it's blowing about 30 kt, maybe a little more, and the temperature is about 55 degF (13 degC), so I've got a lined jacket instead of the shell I use to keep off the morning chill.

We'll either have lovely spring days with blue skies and comfortable temperatures or we'll have windy, cool spring days or a combination of the two. This is why I suggest layers--a short-sleeved shirt with a wind-proof light jacket over light to medium-weight slacks or trousers. Just in case I've been overly optimistic about the rain, an umbrella might not be a bad idea. However, even at its worst, the weather shouldn't be terrible, just a bit uncomfortable. It is Spring, a freeze is unlikely, and trees and bulbs are flowering. There may even be some wild flowers to see, although we didn't get enough rain in the winter to make a big show and it's too early for the California poppies.

Attached in MS Excel format is the almost-final version of the schedule (agenda). If you can't read this, there's a version with CSV comma-delimited text (agendatxt), although I'm skeptical about its readability. Flat text doesn't seem to be an option.

However, it probably doesn't much matter, as long as you show up at 0800 or so on Tuesday. Everyone getting this e-mail will be on the list for the USAF guards to admit, so there shouldn't be a problem.

I'm looking forward to seeing everyone and I think we're going to have a good time.

We will be allowed to see the SR-71s; I'm now negotiating whether we will be allowed to look inside the cockpit.

Tom Cord is arranging a social event at the Officers' Club (Club Muroc), probably on Tuesday evening. It's not an official event, but attendance is encouraged.

The Weather Channel is currently predicting "cool" temperatures and rain showers on Tuesday, moving out on Wednesday, and warmer on Thursday. This is coming down out of the Gulf of Alaska and may miss us, but probably won't since I've gathered so many people together here. I interpret "cool" as around 50 degF, by the way.

Regards,
Mary

PS. If anything desperate requires you to contact me over the weekend, you may call me at 661 942-7434. MFS

To: Members of RC Branch

There will be a workshop "Pilot-Induced Oscillation Research: Status at the End of the Century" here at Dryden on 6-8 April. I have attached the almost-final agenda (in Excel).

Pat thinks it important that members of the branch participate as much as possible in this and I'd like to invite everyone to stop by for as many presentations and discussion as you can manage. The people speaking and attending are all well known and highly regarded, so we'll have a chance to hear the latest news from the people who really know.

Nothing special is required for Dryden personnel to attend. None of the material presented is classified or limited in distribution. I will have copies of the material presented for those who can't make it, although the discussion is often more interesting and informative than the actual presentations.

I hope to see many of you there.

Mary

Thursday 8 April

Session V: Real-Time Detection of PIO. Moderator Daniel Biezad, Cal Poly, San Luis Obispo.

Do We Need Onboard Detection of PIO? David B. Leggett, Air Force Research

Real Time PIO Detection and Compensation. Chadwick J. Cox, Accurate Automation Corp. and Carl Lewis, Robert Pap, Brian Hall, Charles Suchomel

PIO Detection with a Real-time Oscillation Verifier (ROVER). David G. Mitchell, Hoh Aeronautics Inc.

Pilot Opinion Ratings and PIO. Michael Nelson and Tom Twisdale, USAF Test Pilot School

The Need for PIO Demonstration Maneuvers. Vineet Sahasrabudhe and David H. Klyde, Systems Technology, Inc. and David G. Mitchell, Hoh Aeronautics Inc.

Session VI: Flight Results. Moderator John Hodgkinson, Boeing Phantom Works

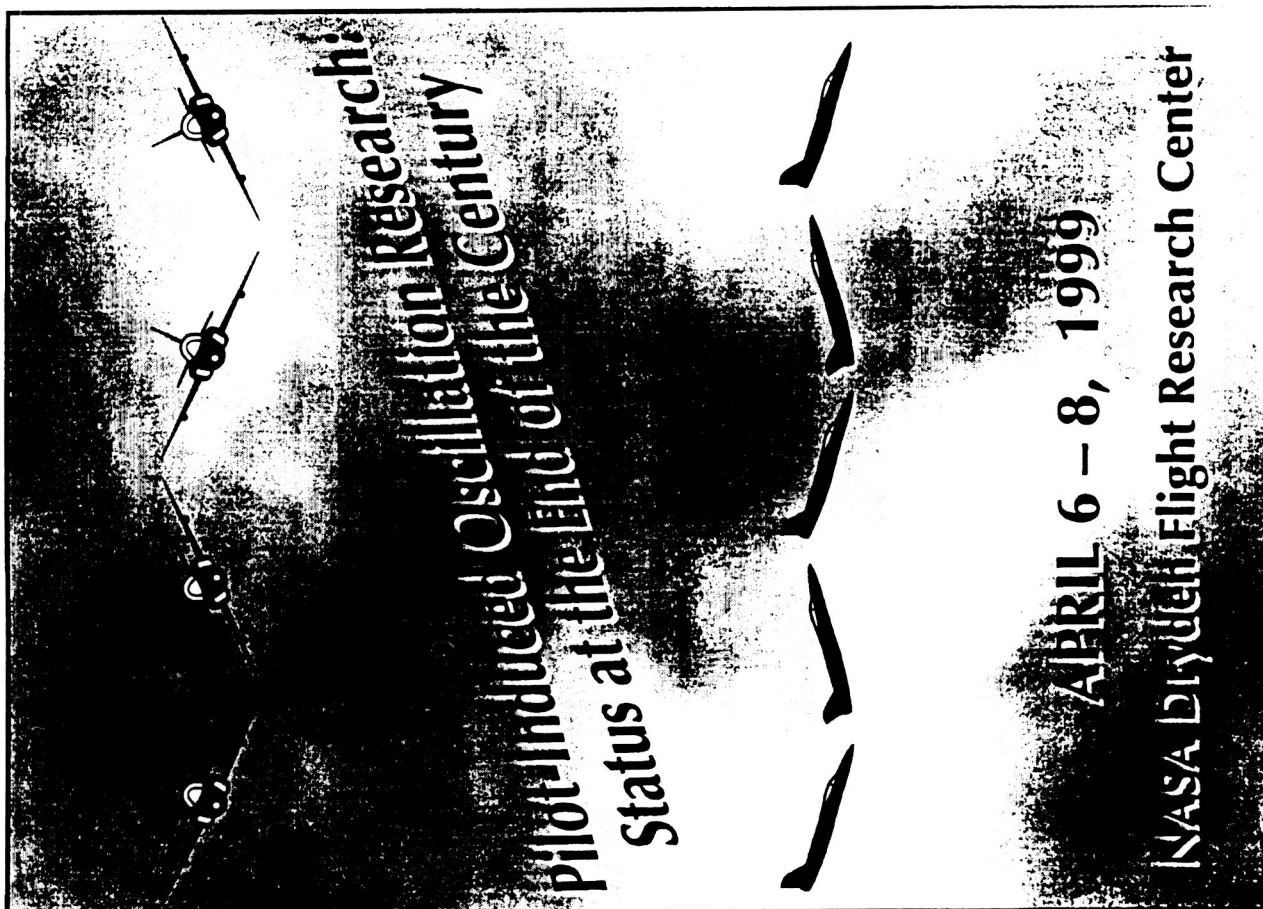
T-45 Ground Handling Qualities. James G. Reinsberg, Boeing St Louis

Extraction of Pilot-Vehicle Characteristics from Flight Data in the Presence of Rate Limiting. David H. Klyde, Systems Technology, Inc. and David G. Mitchell, Hoh Aeronautics Inc.

Comparison of PIO Severity from Flight and Simulation. Thomas J. Cord, Air Force Research Laboratory

A Summary of the Ground Simulation Comparison Study for Transport Aircraft. Terry von Klein, Boeing Phantom Works

Real Experiences in the Frequency Domain. Andrew Markofski and Randall E. Bailey, Veridian Engineering



Tuesday 6 April

Registration (1 hour)

General Remarks Mary Shafer, Workshop Organizer

Welcome by Mr. Kevin Petersen, Director, Dryden Flight Research Center

Session I: PIO Criteria, Moderator: Thomas Cord, Air Force Research Laboratory

Modeling the Human Pilot in Single-Axis Linear & Nonlinear Tracking Tests. Y. Zeyada and Ron Hess, University of California, Davis

Criteria for Category I PIOs of Transports based on Equivalent Systems and Bandwidth. Kenneth F. Rossitto and Edmund Field, Boeing Phantom Works

Bandwidth Criteria for Category I and II PIOs. David G. Mitchell, Hoh Aeronautics, Inc.

Designing to Prevent PIO. John C. Gibson, Consultant, British Aerospace

Session II: Simulation of PIO, Moderator: Louis Knotts, Veridian Engineering

Replicating HAVE PIO on the NASA Ames VMS. Jeffery Schroeder, NASA Ames Research Center

Replicating HAVE PIO on Air Force Simulators. Ba T. Nguyen, Air Force Research Laboratory

Prediction of Longitudinal Pilot-Induced Oscillations Using a Low Order Equivalent System Approach. John Hodgkinson and Paul Glessner, Boeing, and David Mitchell, Hoh Aeronautics Inc

Recommendations for Future PIO Simulation Studies. Brian K. Stadler, Air Force Research Laboratory

**The workshop will begin at 0800 and end at 1600 each day.
Lunch will begin at about 1115 and last 45 minutes to 1 hour.
There will be a morning and afternoon break.**

Wednesday 7 April

Session III: Regulatory Issues, Moderator: Al Lawless, National Test Pilot School

FAA's History with APC. Guy C. Thiel, FAA

PIO and the CAA. Graham Weightman

PIO Flight Test Experience at Boeing – and the Need for More Research. Brian P. Lee, Boeing Commercial Aircraft Co.

The Effects on Flying Qualities and PIO of Non-Linearities in Control Systems. Edmund Field, Boeing Phantom Works

Mitigating the APC Threat - a work in progress. Ralph A'Harrah, NASA Headquarters

Session IV: Flight Research and Test, Moderator: Mary Shafer, NASA DFRC

Flight Testing for APC: Practice at Airbus. Pierre Poncelet, Aerospatiale, and Fernando Alonso, Airbus

The Prediction and Suppression of PIO Susceptibility of Large Transport Aircraft. Rogier van der Weerd, Delft University of Technology

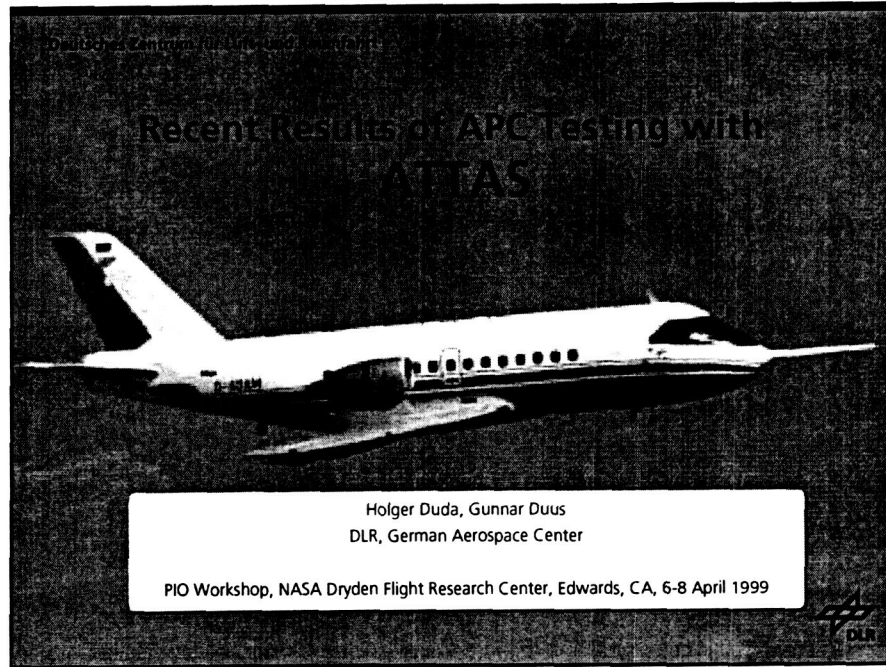
Space Shuttle Orbiter Landing PIO. Pat Forrester, NASA Johnson Space Center

Flight Testing for PIO. Ralph H. Smith, High Plains Engineering

Use of In-Flight Simulation for PIO Testing and Training. Michael Parrag, Veridian Engineering

A Method for the Flight Test Evaluation of PIO Susceptibility. Tom Twisdale, USAF Test Pilot School

Appendix 2



This presentation gives an overview about results of PIO-investigations obtained from a flight test program on DLR's flying simulator ATTAS (Advanced Technologies Testing Aircraft System). ATTAS is a small civil a/c, which has been developed as a full Fly by Wire In-Flight-Simulator with a safety pilot in the right seat.

(This presentation has been prepared by Dr. Holger Duda and Gunnar Duus and myself)

Contents

- Aircraft-Pilot Coupling
- Prediction of APC
- The OLOP Criterion
- Recent Flight Test Experiments with ATTAS
- Data Analysis Techniques for APC Assessment
- Conclusions
- Future Activities



PIO Workshop, NASA Dryden Flight Research Center, Edwards, CA, 6-8 April 1999

The contents:

- 1. The aircraft-pilot coupling phenomenon is illustrated briefly. Criteria for APC-prediction are discussed, emphasizing the OLOP-criteria for prediction of nonlinear APC.
- Thereafter the main results of recent ATTAS-experiments, with respect to experiment-design, results and data analysis concepts for APC assessment are discussed.
- Finally the conclusions and DLR's plans for the future are given.

Aircraft-Pilot Coupling (1)

- Aircraft-Pilot Coupling (APC) is a highly adverse man-machine problem due to disharmonic pilot control inputs.
- The meaning of the acronym PIO was changed from *pilot-induced oscillation* to *pilot-involved oscillations* in order not to blame the pilot.
- Non-linear effects in the flight control system can cause APC problems (*flying qualities cliff*).
- The APC phenomenon contains three main elements: the pilot, the aircraft, and the trigger.
- APC is no pilot failure, but a failure in the flight control system design process.

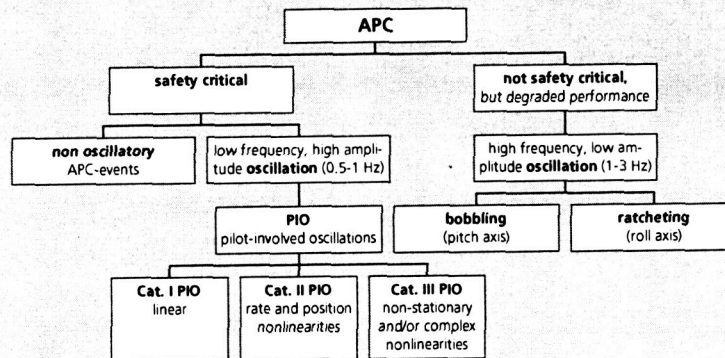


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- The above list contains the most important key words when talking about APC.
- There is a strong agreement that APC is a highly adverse man-machine problem due to disharmonic pilot control inputs.
- The expression APC was introduced to replace the acronym PIO first. Today APC has a more general meaning than PIO
- We all know well that nonlinear effects in the FCS can trigger APC. This is commonly illuminated by the FQC metaphor
- Further more we can state that an APC contains 3 elements: pilot, a/c and trigger. Pilot is obvious, since without the pilot in the loop no APC is possible. The a/c is represented by the complete Flight Control Systems. The trigger can have different forms, such as NL-effects, or increased task elements, but always causes a sudden change in the closed loop a/c-pilot system dynamics resulting in a misadaptation of the pilot.
- Last but not least: APC is no pilot failure, but a failure in the flight control system design process.

Aircraft-Pilot Coupling (2)

Classification



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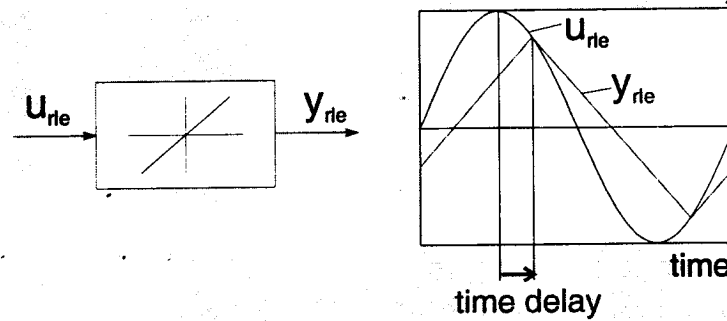
This diagram shows a simple classification (not complete). We can see safety critical and not safety-critical types of APC.

Not critical: We have e.g. the low amplitude-high frequency oscillations bobbling and ratcheting

Critical.: Distinguish between non-oscillatory and oscillatory (where we have PIO three categories)

Aircraft-Pilot Coupling (3)

Rate saturation is the dominating nonlinear effect in modern flight control systems triggering APC (Category II PIO)



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- The history of aviation has shown that Rate Saturation is the dominating nonlinear effect in modern flight control systems triggering APC (Category II PIO). This was the background for defining an individual category for APC caused by Rate Limiters > category II PIO.
- The major problem with Rate Saturation is that an additional time delay is introduced after Rate Limiters onset. The further point is that this additional delay is not constant but amplitude dependent.

Prediction of APC (1)

The main objective is to predict potential APC problems in the design phase of the flight control system.

For that task

several APC prediction criteria are available, such as Neal-Smith, Bandwidth, Phase Rate, Smith-Geddes,

and

a comprehensive handling qualities data base is available, such as the flight test programs Neal-Smith, LAHOS, HAVE PIO, HAVE CONTROL,

but

most criteria and data bases only address linear effects due to filters and time delays in the flight control system causing a *high frequency phase rolloff*.

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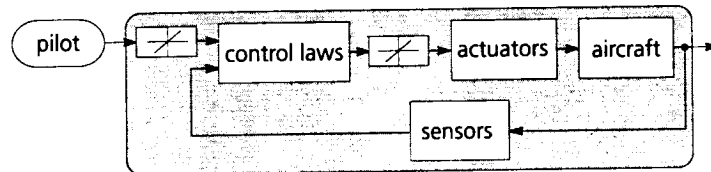
The objective of this presentation is to discuss means and methods used to predict potential APC problems in the design phase of the flight control system.

For that task several APC prediction criteria are available, such as Neal-Smith, Bandwidth, Phase Rate, Smith-Geddes.

But most criteria and data bases only address linear effects due to filters and time delays in the flight control system causing a high frequency phase-rolloff. The high frequency phase-rolloff is the main effect causing category I PIO.

Prediction of APC (2)

Implementation of Rate Limiters in Flight Control Systems



Feedback loop:

- Protecting the actuators against overload
- Defining the maximum rate independent of the flight condition

Forward path:

- Preventing a saturation of the feedback loop limiters due to high pilot input rates

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But what about category II ?

Let us first have a look at typical implementations of Rate Limiters in modern FCS. We have two typical locations: In the feed-back loop and in the forward path.

In order to predict APC due to these Rate Limiters we have developed the OLOP criteria at DLR.

The OLOP Criterion (1)

OLOP means the **Open Loop Onset Point** of a rate limiter in an aircraft-pilot loop, which is plotted in a Nichols chart.

OLOP is a criterion to predict handling qualities problems due to rate limiting in the flight control system (category II PIO).

OLOP is applicable to the roll, pitch and yaw axes for rate limiting elements in the forward path or in the feedback loop of the flight control system.

OLOP has been developed by DLR based on the describing function technique; the intensity of the jump resonance is highly dependent on the OLOP-location.

*... The **OLOP** criterion has all the hallmarks of the present author's methodology for practical design guidance ...*

John Gibson, 1999



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OLOP means Open Loop Onset Point.

The **OLOP** criterion is capable to predict category II PIO due to rate saturation effects.

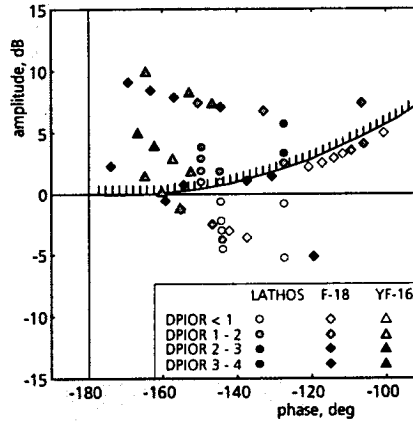
It is applicable to all related problems.

OLOP has been developed, based on the Nichols amplitude/phase diagram. It has been shown that the intensity of the jump resonance due to Rate Limiting onset is highly dependent on the **OLOP**-location in a Nichols chart. For **OLOP** application no Describing Function technique is required.

The OLOP Criterion (2)

Validation of the OLOP Criterion

- Flight simulator experiments on FFA's ground based simulator FOSIM*.
- Five experienced test pilots performed 342 simulator runs.
- *DPIOR* means the difference between linear and non-linear PIO ratings; all runs were done with and w/o rate limiting.
- Significant correlation was found between the DPIORs and the OLOP criterion.



*FOSIM: Forskningssimulator

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Here some high-level information about OLOP are given:

OLOP has been validated by special simulator experiments

FOSIM simulator was used within a collaboration with the Swedish FFA.

342 test runs (using different configurations in the roll axis based on LATHOS, F-18, YF-16 test pilots) with five test pilots were made.

The results are shown above.

You can see a significant correlation between the OLOP location and the DPIORs

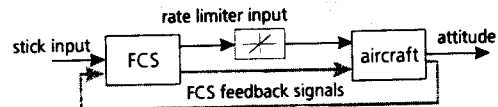
It is important to correlate the DPIORs with OLOP since OLOP only predicts APC due to Rate Limiters effects. It is not correlated with the category I PIO criteria.

The OLOP Criterion (3)

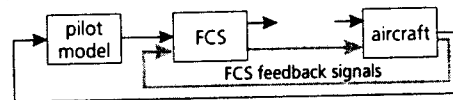
Determination of OLOP

1. Linear frequency response from stick input to attitude:
→ pilot model gain
2. Linear frequency response from stick input to rate limiter input:
→ onset frequency ω_{onset}
3. Linear frequency response of open loop system (loop opened at the rate limiter):
→ OLOP: [phase, gain]@ ω_{onset}

Closed Loop Aircraft System



Open Loop Aircraft-Pilot System



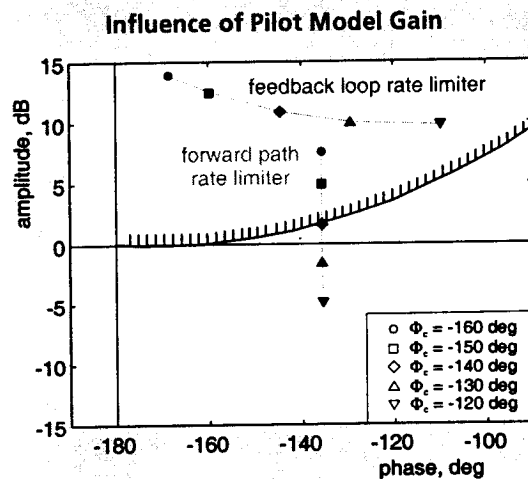
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For OLOP application three linear frequency responses are required.

1. From stick to attitude (this is also required for Neal-Smith or Bandwidth criteria) used for the pilot model
2. From stick to rate limiter input > Omega-onset
3. Open loop system including pilot model.

The OLOP Criterion (4)



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One special chapter is the pilot model. It is proposed to use simple gain models based on the crossover phase angle Ξ_c . Further more a range of pilot gains should be investigated.

There are two example configurations, one with Rate Limiter in the feedback-loop and one with Rate Limiter in the forward path. This is category II PIO prone only for very high pilot gains, which means aggressive pilots. The other configuration (RL in FB-loop) is category II PIO prone for the entire pilot model gain range.

Here we will probably have a problem.

The OLOP Criterion (5)

Documentation

- Duda, H.: *Effects of Rate Limiting Elements in Flight Control Systems - A New PIO-Criterion*, AIAA-Paper 95-3204, 1995.
- Duda, H.: *Prediction of Pilot-in-the-Loop Oscillations due to rate saturation*, Journal of Guidance, Navigation, and Control, Vol. 20, No. 3, 1997.
- Duda, H.: *Flying Qualities Criteria Considering Rate Limiting*, DLR-FB 97-15, 1997.
- Duda, H., Duus, G.: *New Handling Qualities Database on PIO due to Rate Saturation*, DLR-FB 97-53, 1997.
- Duda, H., Duus, G., Hovmark, G., Forssell, L.: *New Flight Simulator Experiments on PIO due to Rate Saturation*, AIAA-Paper 98-4336, 1998.
- Duus, G., Duda, H.: *Analysis of the HAVE LIMITS Data Base using the OLOP Criterion*, to be presented at the 1999 AIAA-AFM Conference.

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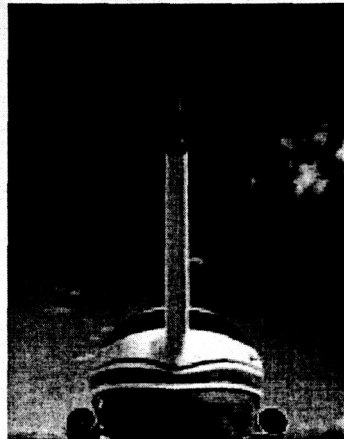
Here a list of the most important documents

- 1995 was the first, where the idea was presented, but the criterion was not fully developed and no data base was available.
- A very extensive report is this one, but in German
- The next papers describe the data base
- And finally we analysed the HAVE LIMITS data base. The results are presented at the 1999 AIAA conference in Portland by Gunnar Duus.

Recent Flight Test Experiments with ATTAS (1)

Objectives

- Final Validation of the OLOP criterion using flight test data. Identification of pilot model gains in the pitch axis.
- Testing automatic code generation tools for software implementation on the ATTAS experiment computer (Simulink *Real-Time Workshop*).
- Improving flight test evaluation and analysis techniques for APC assessment.



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The ATTAS experiments:

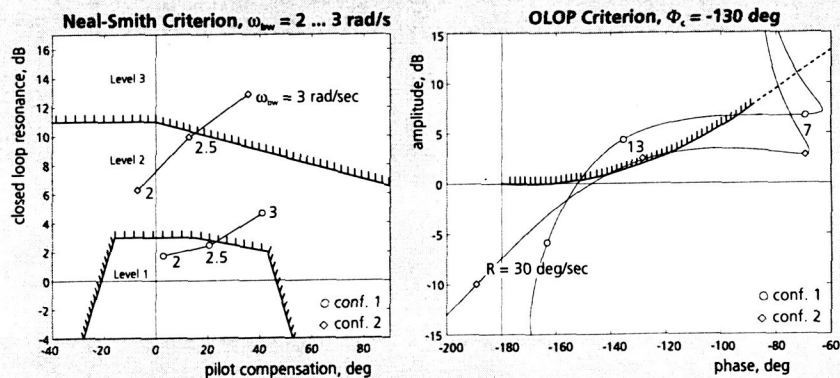
There were three objectives:

Although we consider the OLOP criteria as ready we wanted a final validation, especially to get some more experience in the pitch axis.

We did all the design and analysis work in the Matlab/Simulink environment, check Real Time Workshop. Last but not least we plan to develop further our flight test data analysis concepts for APC assessment.

Recent Flight Test Experiments with ATTAS (2)

Experiment Design (Pitch Axis)



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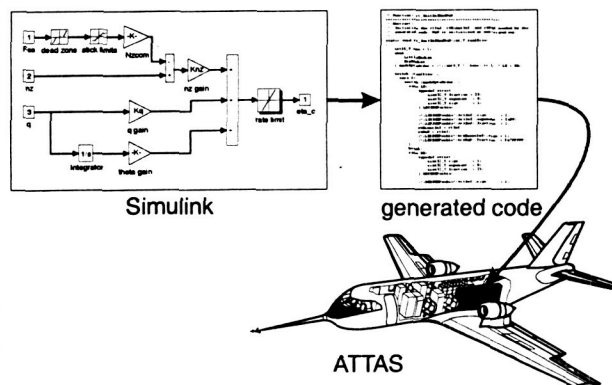
We designed the experiment based on a set of criteria. I will concentrate my talk on the pitch axis, but we did the same thing in the roll axis too.

In the pitch axis we used the N/S and C* criteria in order to define the linear system dynamics and OLOP for the behaviour after Rate Limiters onset. We defined baseline configs. one in L1 and one in L2/3. This is depending on the band width (BW) when N/S is applied. For this type of a/c BW of 2,5 is most relevant. For investigation of Rate Limiter effects we applied 3 max. rates (7, 13 and 30 deg/s) for the elevator deflection.

The diagram shows see the OLOP locations. It is interesting, that with increasing max. rate the category II PIO potential seems to be bigger. This is a point where we were not able to clarify this by the flight test results. We assumed a time delay responsible for this result.

Recent Flight Test Experiments with ATTAS (3)

Software Implementation via Simulink Real-Time Workshop



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This diagram depicts our s/w implementation concept. We developed simple controllers under Simulink. In the pitch axis it is nz or C^* law, containing q and nz feedback and one integrator.

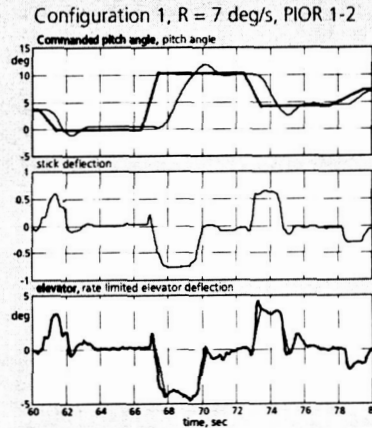
Using the Real Time Workshop we simply pushed a button and got a C-code which is implemented on the ATTAS experiment computer.

This is a very exciting technique which we did first time for these experiments. Quite a lot of s/w adaptation work was required, but we now have a excellent basis for future experiments.

Recent Flight Test Experiments with ATTAS (4)

Experiment Results

- Software implementation via *Real-Time Workshop* works well and provides a very good basis for future experiments.
- Significant correlation between pilot comments and predictions based on the criteria was obtained.
- It is very "difficult" to produce a Category II PIO in the pitch axis for a basically stable aircraft. In the roll axis Category II PIO is more likely.
- Pilot gains were much smaller than expected, especially in the pitch axis.



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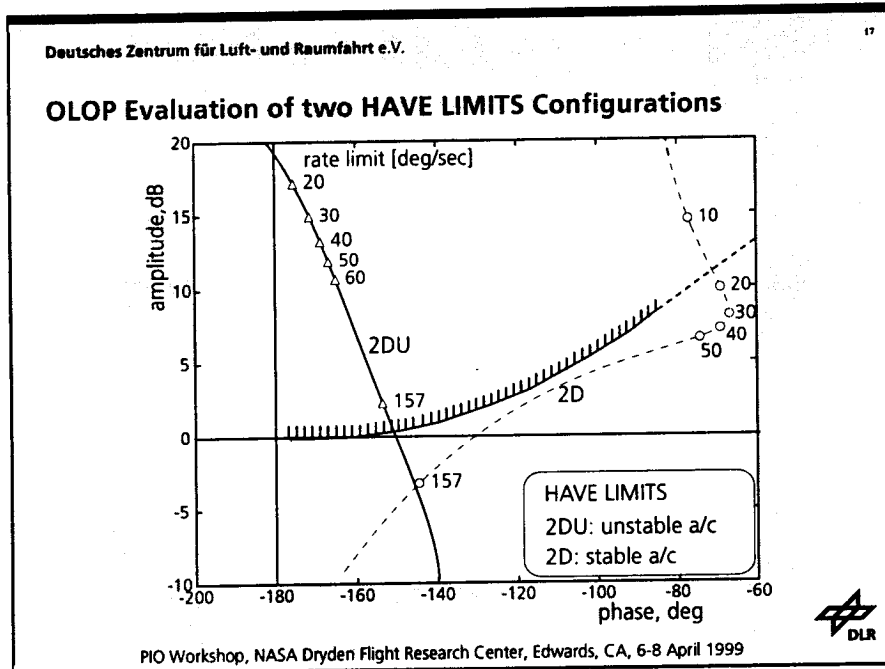
This chart shows the main experiment results:

First the s/w implementation was greatly facilitated using Real Time Workshop.

A significant correlation between pilot comments and predictions based on the criteria was obtained

A very interesting result is, that it is "difficult" or very unlikely to get category II PIO in the pitch axis with stable aircraft.

There is one example - a run with a max. rate of 7 deg/s, which is very low. - The pilot gave a PIOR of 1-2. Here is one explanation: The depicted example shows a tracking task with a commanded pitch angle. Pilot activities show that the pilot gains were much smaller than expected. I will come back to this point later.



Here is one more chart to confirm the statement that category II PIO for stable a/c is very unlikely - the HAVE LIMITS program (to be presented on AIAA 1999).

You see two configs. from HL evaluated with the OLOP: 2D represents a stable a/c, while 2DU represents an unstable a/c. 2D runs into the dangerous area only very low Rate Limitations, while 2DU is category II PIO prone even for quite high max. rates.

This result is well in-line with the FT results obtained in the HAVE LIMITS program. Gunnar Duus will give more details on this study in Portland.

Data Analysis Techniques for APC Assessment (1)

The objective is to develop procedures for APC-Assessment based on flight test data complementary to the pilot ratings.

Approach

- Identification of simple aircraft and flight control system (FCS) models from the flight test data.
- Evaluation of handling qualities criteria using the identified aircraft and FCS models.
- Comparison of criteria results with pilot comments.
- Identification of pilot models for the evaluation of the OLOP criterion.

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Now I come to the data analysis. The objective is to develop procedures for APC-Assessment based on flight test data complementary to the pilot ratings. The pilot rating is always subjective and it is quite easy not to find a "hidden weakness". So numerical data analysis is an important factor in order to maximise flight safety.

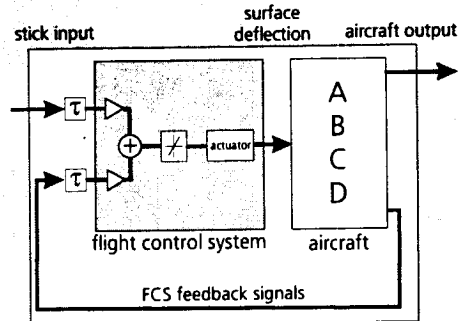
Our approach is to identify simple a/c- and FCS- models and evaluate Handling Qualities criteria and compare the numeric results with the pilot comments.

Furthermore we identify simple pilot models for application of OLOP.

Data Analysis Techniques for APC Assessment (2)

Identification Concept

- a) Fourier transforms from stick input to aircraft output signals; approximation of transfer functions
- b) Linear aircraft models in the time domain from control surface deflection to aircraft output signals.
- c) Linear aircraft-FCS models in the time domain from control stick input to aircraft output signals.
- d) FCS time delays using the results from b) and the known FCS gains and rate limits; to be used for OLOP evaluation.



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I will now discuss different concepts for a/c-FCS mode identification.

The first one works in frequency domain. Transfer functions are approximated to the fast fourier transforms of the test data.

Method b) is only required for d): it means the identification of linear a/c models using surface deflection as input and a/c reaction as output.

Method c) uses stick signals as input. An equivalent time delay is estimated.

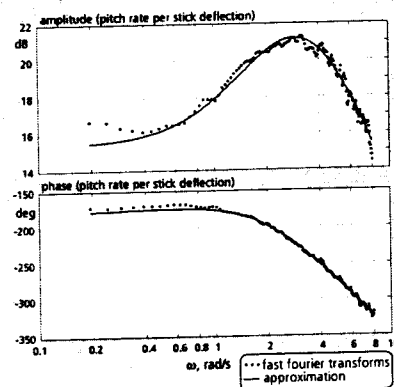
For method d) only delays in the forward path and feedback loop of the FCS are identified, while the FCS gains, the maximum rate of the limiters and the linear a/c models are fixed.

This technique is required to evaluate OLOP from FT data. OLOP can not be evaluated correctly based on method a) and c) (exception: rate limiters in the forward path).

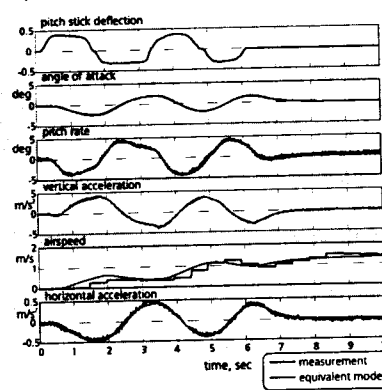
Data Analysis Techniques for APC Assessment (3)

Identification of Aircraft-FCS Models, methods a) and c)

a) Frequency Domain Identification



c) Time Domain Identification (Equivalent Model)



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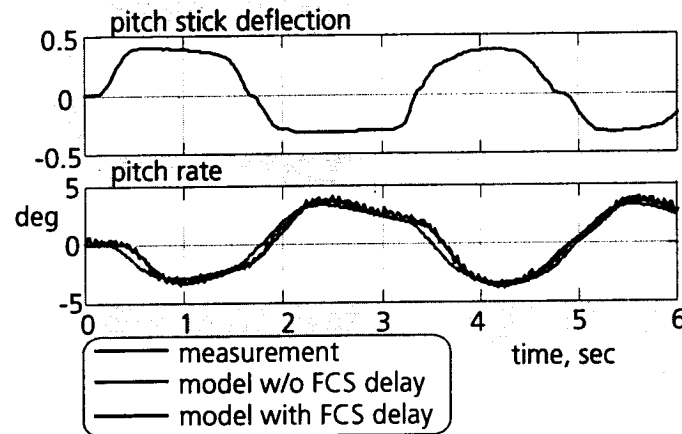


On this chart methods a) and c) are illustrated.

Right: Method a) is a little bit more difficult to apply, you have to decide about the frequency range to be considered. In this case we did the approximation up to a frequency of eight rad/s.

Left: Here you see the identification of an equivalent linear model. Here we have a 3211 input signal, so that it is difficult to include the phugoid motion due to the short time of the run.

It has been shown that an PID of the tracking task (duration = 120 s) is favourable.

Data Analysis Techniques for APC Assessment (4)**Identification of FCS Time Delays, Method d)**

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This chart shows one PID result of concept d)

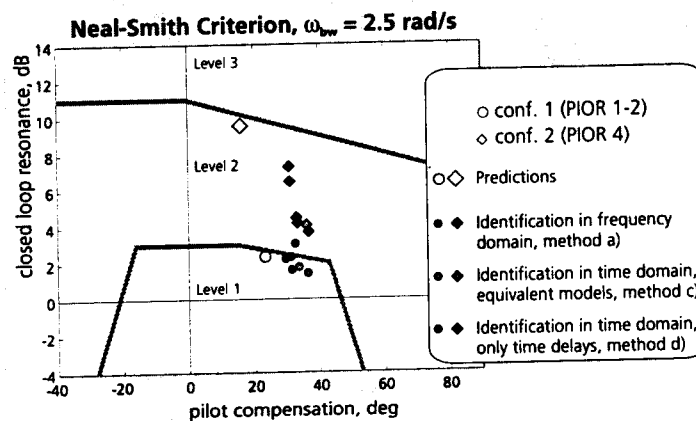
The red curve represents the a/c-FCS model response without time delay.

The blue curve the response with time delays.

You see that we have a better matching with delay.

Data Analysis Techniques for APC Assessment (5)

Comparison of Different Identification Concepts



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This chart shows the results of the three Identification concepts for the pitch axis configs. Additionally we see the predictions based on the model and assumed time delay we used before FT. The main cause for the difference between Identification and prediction is the assumed delay.

For config 1 we got very consistent results, but we have some scattering for config 2. This is because this configuration is quite sensitive to additional delays.

Method d) (only identification of delays) provides the most consistent results compared to the pilot ratings. However we are not quite clear about this config. We need to do some further analysis and FT.

Data Analysis Techniques for APC Assessment (6)

Identification of Pilot Model Gains

Approach

Parallel simulation of the closed loop aircraft pilot system.

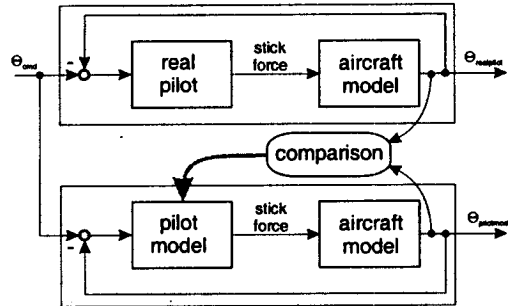
Manual adjustment of pilot gain in order to get "similar" closed loop performance, such as damping and overshoot.

Results

Crossover phase angles for all configurations:

pitch axis: -90 to -100 deg

roll axis: -110 to -120 deg



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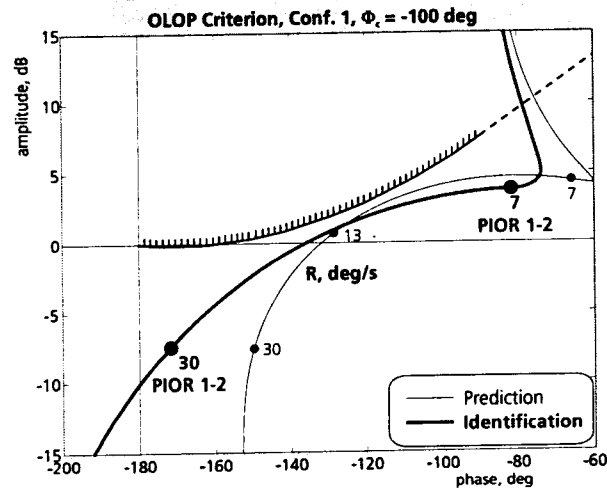


For the evaluation of OLOP we need simple pilot models. For that purpose we do a parallel simulation of the closed loop a/c-pilot model. The input model gain is adjusted manually in order to get "similar" closed loop performance, such as damping and overshoot.

In this case we got crossover phase angles significantly lower than expected. For experiment design we assumed -130 deg as medium gain.

In the roll axis this is slightly higher.

Data Analysis Techniques for APC Assessment (7)



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The identified a/c-FCS and pilot models are used for evaluation of the OLOP criterion. This chart shows config 1- the predicted and identified model for different max. rates.

You see that OLOP does not predict any category II PIO problems, which is well in-line with the pilot comments. The pilot rated this config with PIOR 1-2 for 30 and 7 deg/s max. rate.

We did not fly the 13 deg/s case.

Conclusions

- Flight test experiments with ATTAS were conducted in order to improve the knowledge base on the OLOP criterion, to test new software implementation procedures and flight test data analysis techniques.
- The pilot comments obtained are correlated with the predictions of the criteria (OLOP, Neal-Smith).
- Software implementation via *Real-Time Workshop* (Simulink) works well and provides a good basis for future experiments.
- Different concepts for flight test data analysis were evaluated; the OLOP criterion was successfully evaluated on the basis of the identified aircraft and flight control system models.

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Conclusions:

We did Flight test experiments with ATTAS in order to improve the knowledge base on the OLOP criterion especially in the pitch axis, to test new software implementation procedures and to improve flight test data analysis techniques.

The pilot comments obtained are correlated with the predictions of the criteria (OLOP, Neal-Smith).

Software implementation via Real-Time Workshop (the C-code generator of Simulink) works well and provides a good basis for future experiments.

Different concepts for flight test data analysis were evaluated; the identified aircraft and pilot flight control system models.

Future Activities

The flight test experiments presented have prototype character; the work is going to be continued with respect to

- Experiments with more APC prone configurations, such as aircraft with relaxed static stability.
- Testing of on-line APC detection and warning algorithms.
- Evaluation of phase compensation filters in order to reduce the time delay due to rate limiting.
- APC demonstration maneuvers.

Long Term Objective

A standard for APC testing of highly augmented aircraft

Criteria to Simulation to Flight Test – and Vice Versa

David G. Mitchell
Technical Director
Hoh Aeronautics, Inc.

Pilot Induced Oscillation Research Workshop
NASA Dryden Flight Research Center
7 April 1999



Outline

- Steps for minimizing PIO risk
- Assessing risk if a PIO occurs
- A possible PIO rating system
- Pilot variability in PIO simulation
- Some recommendations



Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
3. Use criteria to focus preliminary simulations
4. Use early flight data to update sim. model
5. Repeat steps 1 - 4
6. Use simulation to apply criteria for large inputs
7. Use criteria to focus preliminary flight tests
8. Use real-time onboard detection for early warning
9. Repeat steps 1 - 8



Be Prepared for PIO

- Military procurements represent a dichotomy:
 - Projects adopt success-oriented scheduling
 - Evaluators expect to encounter PIO in flight test
- PIOs will almost always occur
 - Should not be a surprise
 - Testing must be adopted to look for them
- The more advanced the aircraft (unstable, multiple effectors, multi-purpose effectors, complex augmentation) the greater the potential for catastrophic PIO



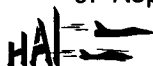
Be Prepared for PIO (concluded)

- Pilots must be a part of the process
 - Familiar with the phenomenon
 - Aware of potential through all phases of testing
- PIO is not an operationally relevant event
 - Test pilots' job is to go beyond normal operations
 - If test pilot won't push the airplane, rest assured that some unsuspecting fleet pilot will
 - Any flight test can be a test for PIO tendency
- If a PIO occurs, there must be a way to assess risk of continuing flight testing before a fix is found



Steps for Minimizing PIO Risk

1. Be prepared for PIO
- 2. Apply criteria to design**
 - As early as possible in design process
 - If you apply valid criteria and your airplane fails, it doesn't mean the criteria are bad
3. Use criteria to focus preliminary simulations
4. Use early flight data to update sim. model
5. Repeat steps 1 - 4
6. Use simulation to apply criteria for large inputs
7. Use criteria to focus preliminary flight tests
8. Use real-time onboard detection for early warning
9. Repeat steps 1 - 8



Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
- 3. Use criteria to focus preliminary simulations**
 - Don't spend time in areas where criteria are easily met
 - If criteria predict PIO -- fix the design!
4. Use early flight data to update sim. model
5. Repeat steps 1 - 4
6. Use simulation to apply criteria for large inputs
7. Use criteria to focus preliminary flight tests
8. Use real-time onboard detection for early warning
9. Repeat steps 1 - 8



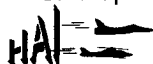
Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
3. Use criteria to focus preliminary simulations
- 4. Use early flight data to update sim. model**
 - It should contain all known nonlinearities and limits
- 5. Repeat steps 1 - 4**
6. Use simulation to apply criteria for large inputs
7. Use criteria to focus preliminary flight tests
8. Use real-time onboard detection for early warning
9. Repeat steps 1 - 8



Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
3. Use criteria to focus preliminary simulations
4. Use early flight data to update design model
5. Repeat steps 1 - 4
- 6. Use simulation to apply criteria for large inputs**
 - Frequency sweeps to control limits
 - Even if sim. is doubtful for PIO, it can be useful for applying inputs beyond those considered safe in flight
7. Use criteria to focus preliminary flight tests
8. Use real-time onboard detection for early warning
9. Repeat steps 1 - 8



Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
3. Use criteria to focus preliminary simulations
4. Use early flight data to update design model
5. Repeat steps 1 - 4
6. Use simulation to apply criteria for large inputs
- 7. Use criteria to focus preliminary flight tests**
8. Use real-time onboard detection for early warning
9. Repeat steps 1 - 8



Steps for Minimizing PIO Risk

1. Be prepared for PIO
2. Apply criteria to design
3. Use criteria to focus preliminary simulations
4. Use early flight data to update design model
5. Repeat steps 1 - 4
6. Use simulation to apply criteria for large inputs
7. Use criteria to focus preliminary flight tests
- 8. Use real-time onboard detection for early warning**
 - Tomorrow morning
- 9. Repeat steps 1 - 8**



Assessing Risk if a PIO Occurs

- If PIO occurs in the development process, it must **always** be treated with concern
 - Fix the problem!
- It may be necessary, and possible, to continue the development effort
- Risk is a function of several factors:
 - Category of PIO
 - Severity of PIO
 - Frequency of occurrence and duration of PIO



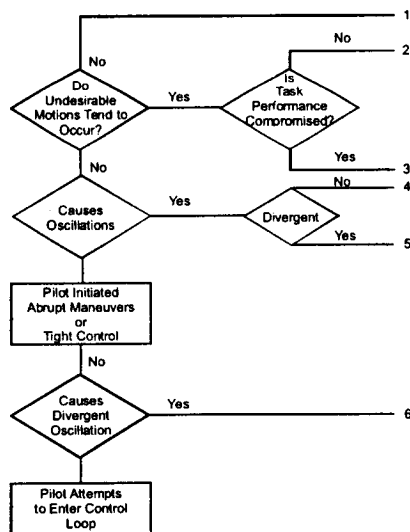
Reducing Risk: Categorize the PIO

- Category I (linear):
 - it should be possible to quickly identify causal factors
 - Lowest risk to continued operation
- Category II (rate limiting or other saturation):
 - More difficult to identify causes
 - Risk depends on other factors:
 - Flight condition/aircraft configuration -- avoidable?
 - Consequence of saturation -- unstable airplane?
- Category III (nonlinear with mode switching):
 - Highest risk, factors similar to Category II



Current PIO Tendency Rating Scale

- Problems with scale
 - Does not mention "tendency"
 - PIOR = 2, 3: not relevant to PIO
 - PIOR = 4: no indication of severity
 - Attempts to mix handling qualities with PIO assessment
- Examples:
 - Pitch bobble (PIOR = 4) with inadequate control power (HQR = 8)
 - Severe (but not divergent) PIO (PIOR = 4) that is unacceptable (HQR = 8)



A Possible PIO Rating System

Severity	Frequency of occurrence	Demands on pilot	Overall assessment
Dangerous (bail out)	Never stopped	Couldn't prevent it (abandon airplane)	What airplane?
Severe (abandon task)	Most of the time	Couldn't prevent it (Abandon task)	Intolerable for the task (fix it)
Moderate (can't ignore it)	Occasional	Prevented or alleviated by technique (task performance compromised)	Objectionable (warrants improvement)
Mild (can ignore it)	Only a very short time	Prevented or eliminated by technique (task performance not compromised)	Tolerable (satisfactory without improvement)
None	Never saw one	No tendency to induce oscillations	What PIO?

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PIO Rating System Allows for Risk Assessment in the Development Process

- Example: PIO Severity vs. Frequency of Occurrence

Severity		Frequency of occurrence				
		Never stopped	Most of the time	Occasional	Only a very short time	Never saw a PIO
Dangerous (bail out)		High	High	High	High	
Severe (abandon task)		High	High	Moderate	Moderate	
Moderate (can't ignore it)		High	Moderate	Moderate	Low	
Mild (can ignore it)		Moderate	Moderate	Low	Low	
None						

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Pilot Variability

- Variability in pilot opinion is well-documented in handling qualities experiments
 - Test pilots have varying backgrounds, expectations, flying styles
 - This is good! Fleet pilots will be even more diverse
- Variability is magnified when it comes to PIO tests and exposure of PIO tendencies
- Monitor pilot performance for tracking tasks
 - Expect variability in performance (example: recent sim.)



Pilot Variability in PIO Simulation

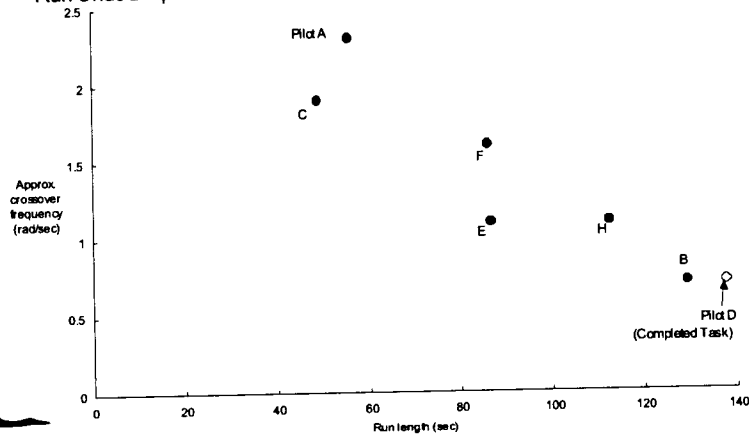
- Example: HAVE LIMITS Config. 2DU, 20-deg/sec RL, discrete tracking task, flown on USAF LAMARS simulator
- Some (minor) differences in setup between sim. and flight
- Results below are typical of sim. (10 pilots total)
 - Different pilots encountered PIO at different rate limits

Facility	Pilot I.D.	HQR	PIOR
NT-33A (Flight)	1	10	6
	2	10	6
	3	10	6
LAMARS (Moving-base simulation)	A	10	5
	B	10	5
	C	10	6
	E	10	6
	F	10	5
	H	10	5



Pilot Variability in PIO Simulation

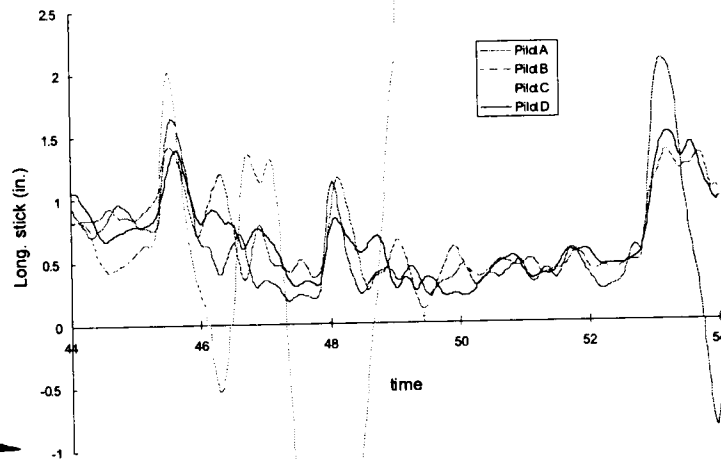
- Plot shows measured crossover frequency (q/q_{error}) from discrete tracking task vs. total run time
 - Task started at $t = 10$ sec, ended at $t = 138$ sec
 - Run ended if pilot encountered rapidly divergent PIO



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Pilot Variability in PIO Simulation

- Ten-second sample of long. stick for two highest-crossover pilots (A and C) and two lowest-crossover pilots (B and D)
 - Pilots A and C consistently show larger, more rapid inputs



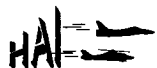
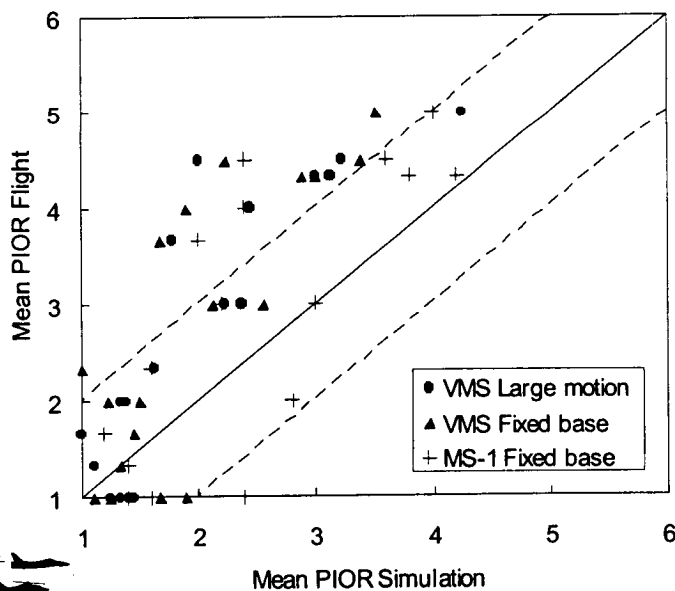
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Amplitude of PIO

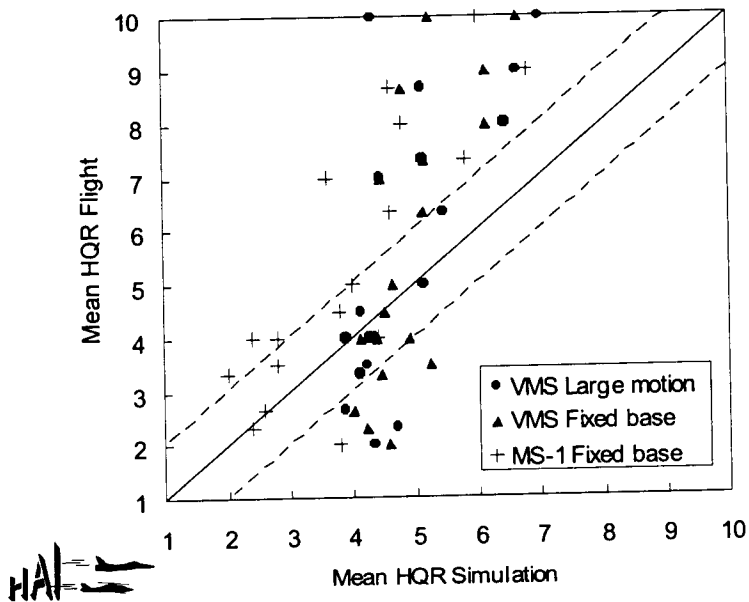
- Monitor time-history data for evidence of PIO
 - Pilots aren't always aware of PIO on simulator
 - Events that seem mild to the pilot may be severe in flight
 - Work with the pilot as much as possible!



HAVE PIO Rating Comparisons: PIOR

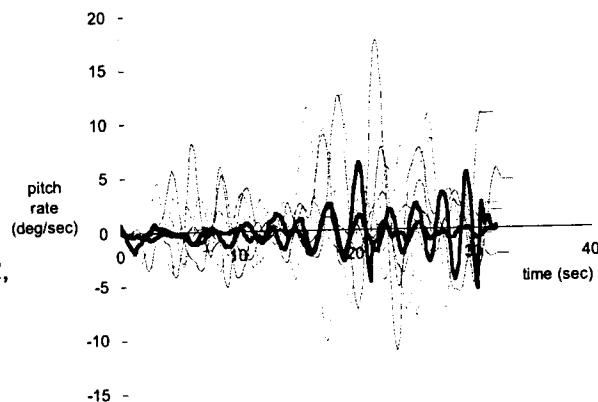


HAVE PIO Rating Comparisons: HQR



PIO May Be More Severe in Simulators

- Black lines: flight program (Pilot A, PIOR 6, HQR 10)
- Red and blue lines: MS-1 simulation (Pilot 2, two sessions, PIOR 4, HQR 6)



Recommendations

- Make maximum use of criteria, simulation, and flight test
- Simulation has value as an adjunct to flight
- Be prepared for PIO
- Assess risk for continuing if PIO is encountered in the development process
- Expect pilot variability
- Look at both qualitative and quantitative information from simulation
 - Ratings tend to be better
 - PIOs may be more severe



Appendix 3

Designing to prevent safety-related PIO

PIO Workshop, NASA Dryden, 6th - 8th April 1999

J C Gibson

British Aerospace Warton (retired), Consultant

Introduction

Though PIO is not a new phenomenon, its current notoriety has been acquired in the past two decades mainly from the all-too frequent serious and sometimes catastrophic examples exhibited in fly by wire aircraft. Such severe examples were a rarity in the earlier "classical" aircraft with conventional control systems. Yet the fly by wire technology had brought with it the power to provide almost any desired handling response qualities. PIOs and sometimes other handling problems of the "high order" type (to distinguish them from the usually much less severe "low order" types possible with conventional dynamics) were actually not generic to the technology as was commonly believed at one time but were inadvertent artefacts of the control system designers. Since the PIO characteristics were "designed in", they can also be "designed out".

The intellectual rigour necessary to prevent PIO by design must be spread out far beyond the discipline of the control law specialists. Section 9 of Reference 1 discusses the team approach essential for the design and evaluation process, and notes the many failures that have resulted from neglecting this. The repeated examples indicate that newcomers to the fly by wire field have found it difficult to believe that the problem could happen to them, and so have not implemented a meticulous anti-PIO design policy. Safety-related, high-order type PIO is not a problem with no practical solution, preventable only by good luck. The author's 1978 paper on the Tornado PIO in 1976 and its solution (Reference 2) was greeted with surprise, since it was not normal in the conference circuits to admit to such a problem even though it was widespread. The latter head-in-the-sand attitude probably contributed to the continuing occurrence of safety-related PIO, and only more recently was the author's example followed by what is now a flood of data and information on the problem.

The author's own brush with PIO and its solution led to a design methodology to eliminate it in future projects. The success of this was demonstrated from the early 1980s onwards by a series of highly unstable aircraft with digital FBW control, namely the Jaguar FBW demonstrator, the EAP demonstrator and the Eurofighter 2000. Each took to the air with a growing certainty that safety-related PIO would not be experienced or even be possible, a certainty that proved to be justified. The rather simple physical principles of control system design for PIO prevention are discussed in Reference 3.

Use and misuse of specifications

Designers are very likely to get into trouble if they simply design to satisfy customer specifications. It is not practical to impose specification criteria for handling qualities design in sufficient detail to ensure good handling qualities while not unnecessarily restricting other design possibilities that may actually improve on the classical response types. It is not the business of a government department to design control systems. Practical specifications provide some "must have" requirements, but one that tries to cover too much ground at once with too few parameters risks allowing unsatisfactory behaviour to slip through if it is used as the only design guidance.

Perhaps the best known example is the specification for short period frequency versus n/α . Level 1 handling has never been achieved with frequencies near the upper limit, except for good landing approach control. The latter is most unlikely with minimum allowable frequencies, but good handling has been achieved at higher speeds with lower frequencies.

Another example in Figure 1 is from generic ASTOVL handling research for the jet-borne hovering phase on a high fidelity motion platform. Two of the cases are plotted on an attitude response mode criterion from the rotary wing aircraft specification ADS-33C. This criterion quantifies the handling by the bandwidth and high order effects by the phase delay. Both cases, assessed in the task of lateral translational control, are nominally second order roll attitude responses with a bandwidth of 6 radians per second. Their actual bandwidth decreases with increasing phase delay, which was created by an additional second order lag to represent high order effects. This generic fourth order model format was derived from a design study for the VAAC Harrier research aircraft and represented its high order system dynamics very accurately.

However, the results were not what the criterion would lead one to expect. In case 1(a), as the bandwidth decreased with increasing phase delay, the translation task handling qualities remained constant. These qualities were found to be related to specific time response characteristics that remained effectively unchanged from the baseline bandwidth case. There was an increasing untidiness in attitude control induced by the high order lag, though the effects were acceptable over the range tested. Case 1(b) with higher bandwidth, despite remaining completely within the criterion Level 1 region, deteriorated into severe attitude control PIO, exacerbated by lateral acceleration forces on the stick and pilot's arm with the cockpit mounted on top of the platform. The cause lay in the high PIO gain of the attitude frequency response, which is not accounted for by this criterion. The only difference between the cases was that 1(a) had a nominal mode damping of 1.0 and 1(b) had a damping of 0.5.

The criterion broadly quantified the handling of Case 1(a), but it was misleading either as a contract specification or as a design criterion when applied to circumstances presumably not envisaged in its original derivation. It is not known if it was tested for responses with low damping, for example, even though this is permitted elsewhere in the specification.

Potential difficulties can be caused by any other limited-parameter criterion. Figure 2 shows the pitch attitude Nichols plots for the YF-17 as tested by Calspan, in the original severely PIO-prone form and the very satisfactory modified version. To the informed eye, the bad and good natures of the respective responses are instantly obvious from the presented detail alone, but it is necessary to have some formalised criteria to quantify this. The modified case was one of the small number of examples with excellent handling around which the author developed the so-called "Gibson criteria" boundaries in Reference 4 from 1982, the one for landing approach being shown in the figure. The boundaries did indeed capture much of the essence of good handling, but were narrowly constrained and were later found to exclude other perfectly acceptable response shapes. Similar problems arose with the so-called "Gibson criteria" time response observations in Reference 4, which again were derived from a fairly limited set of cases. The author also learned the hard way that sometimes others of a dogmatic frame of mind could find it difficult to accept a response that did not entirely satisfy the boundaries "because it violates the criterion", despite his protestations that they were intended as indicative guidelines and not absolute go/no-go limits.

Nevertheless these criteria appear from the literature to have been of assistance to a number of other designers, and were an essential grounding to the author's later design methodology described in Reference 3. In this, there is a much reduced emphasis on attitude frequency response "shape" boundaries because they inherently change their characteristics with increases in true speed and altitude. The nature of pitch behaviour in the "general handling" region of Figure 2 is richly illustrated for design purposes by time responses such as flight path time delay, attitude dropback and pitch rate overshoot, which cannot be quantified directly from the frequency response even though they may be obviously present by visual inspection. On the other hand, while high order PIO tendencies are easily observed by a lag in the time domain pitch acceleration

response, they are more clearly delineated in a detailed analysis of the frequency response characteristics in the "safety-related PIO" region of Figure 2, independently of the general handling. All this is discussed in Reference 3. (Time responses are an excellent design tool, irrespective of their unsuitability for flight test analysis.)

A variety of delay criteria have been promoted, of which phase delay (or the average phase rate in the author's terminology) is the most accurate measure of the actual dynamics that may lead to PIO, particularly of Type 1 though obviously these may in turn lead on into Type 2 or Type 3 PIO. It is doubtful if such criteria have any meaning for analysis of large amplitude responses with non-linear actuation effects, however. The author found it unprofitable to attempt the laborious time response analysis for phase delay in this regime.

The primary importance of phase delay is to indicate a significant lag in the initial rotational acceleration time response to a pilot's control input which may lead to a Type 1 PIO. If this diverges into the actuator saturation regime, the PIO continues at a decreasing frequency which remains uniquely related to the 180 degree lag in attitude as the non-linear effects become more pronounced with increasing amplitude. If on the other hand a large saturated PIO bursts into life with no intervening growth from small beginnings, then it instantly locks on to the PIO frequency in the same way. In neither case is there any significance in the rate of phase angle variation over a range of frequency beyond the PIO, which in effect is phase delay. What does matter is the manner in which the attitude response at the unique PIO frequencies varies from the linear case as the pilot's input amplitude increases.

The handling qualities specifications known to the author do not address the safety-related PIO problem directly, other than to require that it must not occur. These specifications are generally assumed to apply to the linear regime, presumably because they are mostly expressed in terms of parameters suited to straightforward frequency response analysis techniques. The few requirements specifically associated with full amplitude control inputs, which would certainly invoke any actuation and aerodynamic non-linearities, are typically open loop time response requirements such as roll performance, and would not necessarily illustrate any PIO tendency. Nevertheless there is no general exclusion of large amplitude and non-linear conditions from consideration, and indeed *"the effects of the control equipment should not be overlooked"* in calculations or analyses directed towards investigation of compliance with the specifications.

The realm of the safety-related high order PIO

The following is a brief resume of the author's successful experience in high order PIO solution and subsequent elimination by design over the period from 1976 up to the present, extracted mostly from Reference 3.

At the time of the 1976 Tornado landing PIO, there were no criteria or appropriate data generally available to explain it. However, it had clearly grown out of the stick pumping in the landing flare, an activity described by Bihrlé in 1966. He noted that just before touchdown, pilots would often engage in a rapid pitch control oscillation in phase with pitch acceleration, at frequencies well above the short period. The acceleration amplitude was consistently around ± 6.5 deg/sec². Bihrlé concluded that pilots acted this way to generate confidence in pitch control as the speed reduced towards the stall when very precise flight path control was needed for a smooth and safe landing. The activity was also quite subconscious, all pilots being unaware of it.

The author had used the stick pumping theory in the Tornado design process to ensure that there was adequate hydraulic pump flow capacity at idle engine rpm in the landing approach, and in fact found in flight records that pilots did stick pump as predicted. However, the Tornado pitch attitude dynamics differed significantly from previous conventional aircraft. These consistently feature stick pumping at typically 8 to 10 rad/sec resulting in an attitude oscillation that is very

small. The amplitude is usually less than a fifth of a degree peak to peak and is effectively unnoticeable. The Tornado stick pumping frequency was about 3 to 4 rad/sec. and at the nominal acceleration level the attitude would be around 2 degrees peak to peak. Some pilots used larger pumping amplitudes than others. The likely trigger seemed to be that the pilot suddenly became aware of the attitude oscillation, and was presented unexpectedly with a ready-made PIO situation with the attitude already 180 degrees out of phase.

Stick pumping does not trigger PIO in conventional aircraft. The obvious solution at the time was to ensure that the attitude dynamics in the stick pumping frequency region were made to favour the subconscious pitch acceleration pumping activity, and not to encourage the possibility of the unstable pilot-attitude PIO coupling which occurs at similar frequencies. The "synchronous pilot" PIO model proposed by Ashkenas and McRuer around 1964, expressed as a gain element and assumed to apply control in anti-phase to the attitude oscillation, was clearly evident in the Tornado PIO. With no pilot phase contribution, the closed loop instability naturally occurred at the frequency where the aircraft attitude phase lag to control inputs was around 180 degrees. The author concentrated studies on the aircraft dynamics in this region.

Figure 3 shows the calculated Tornado landing case pitch attitude frequency responses for four different pitch control law configurations. The unaugmented mode was rather sluggish but was otherwise perfectly acceptable. It had already become clear that the stick command gain at low speeds in the first augmented version, which experienced the PIO, was too high as it was excessively easy to saturate the pitch control system. The large amplitude ratio at the 180° phase lag frequency meant that large oscillations could easily be generated by quite moderate stick inputs. In the complete absence of any other criterion whatever, the policy was adopted that a stability margin must remain if any pilot again used the same gain as in the accident.

The second control law version, which was nearly in a flight cleared status at the time of the accident, had already halved the PIO response gain at low speeds with its substantial reduction in stick command gain, and was approved for use. The author expressed reservations because the linear dynamic characteristics of the second version were little changed from the first version. The sensation pilots had of having to "feel for the ground" in the first version was caused by a marked lag in the onset of pitch acceleration in the time response, which was much larger than in the unaugmented case where conventional actuator dynamics were the only high order effect. In the second version the transient acceleration lag had been scarcely reduced at all, and some pilots still found a slight imprecision at touchdown. The author's concern was eventually justified by an incipient non-divergent PIO, distinguished in the flight record mainly by the pilot's statement that he had sensed its onset. As the tailplanes were close to their nominal rate limit, the effective safety margin was unacceptably small. Further use of full augmentation for take off and landing was again prohibited until a final solution was developed.

The third version followed the author's embryonic ideas about the importance of the attitude dynamics around the 180 degree phase lag frequency. It further reduced the PIO gain and the transient acceleration lag by speed-dependent scheduling of the lag-lead stick command pre-filter to a unity gain at low speed. The lag-lead was restored at higher speeds and was later redesigned for pitch tracking optimisation. This version has successfully prevented a recurrence of landing PIO since its introduction more than twenty years ago.

Criteria evolution

The concept of the synchronous pure gain pilot model became a powerful tool in the discovery of solutions to high order PIO and design criteria to prevent it. Though the pilot actions were later found to vary from the pure attitude-related gain model, often with highly non-linear behaviour,

the fundamental pilot actions are always tightly synchronised to components of the attitude response. The policy of dealing with safety-related PIO as a specifically localised problem of attitude dynamics complete in itself, separately from considerations of general handling qualities, has proved to be correct and has led to the author's successful design criteria.

The availability after 1978 of the LAHOS data, Reference 5, enabled the development of the preliminary design criterion discussed in Reference 4. This was based on the nominal stick pumping amplitude and the attenuation of the attitude response between the frequencies at 120 degrees (the author's own early version of bandwidth) and 180 degrees phase lag. The first factor is directly related to the PIO frequency at 180 degrees lag, and favours a high frequency value. The second factor was a gain margin of a sort, but did not explicitly define the absolute PIO gain. The Jaguar FBW demonstrator, designed to this and other "Gibson criteria", began flight tests in 1981 with a high degree of confidence that this PIO problem would not occur, justified in the event as it never did. This may have been the first aircraft control system specifically designed to prevent PIO from the outset.

Continued analysis of the LAHOS data resulted in a more coherent and readily identifiable set of parameters enabling a positive approach to elimination of PIO by design. Figure 4 (from a 1986 paper and given in Reference 3) shows the essential differences between "low order-like" responses with no safety-related PIO tendency and "high order-like" responses with severe PIO tendencies. Note that these terms are not usefully related to the actual order of the flight control system. The most severe LAHOS PIO examples were generated by the addition of a single lag pre-filter to conventional dynamics, while it is perfectly possible for a 60th order FCS to show a low order-like response in the critical PIO region. Design criteria based on these observations utilised the phase rate (similar to phase delay but localised to the 180 degree lag PIO frequency) and the PIO frequency as shown in the figure, with a maximum permitted PIO gain of one sixth of a degree per pound of stick force. These criteria, used in the design of the EAP demonstrator, gave even greater confidence that the PIO problem was defeated. This was again justified by its extremely successful 1986 to 1991 flight program in which no PIO occurred.

These criteria were incorporated the formal handling qualities specification for the Eurofighter, which is showing all the excellent handling qualities of the closely related EAP. The design needs of the fixed gain control mode that was used for a small number of initial flights made it necessary to identify handling limits that were acceptable and safe rather than excellent, since naturally this mode could not be optimised for all speeds, especially at touch down. This resulted in further analysis by the author in 1993 of the LAHOS data to identify PIO gain limits to better quantify Level 2 and Level 3 PIO effects, and the phase rate metric was modified to the average phase rate (exactly the same as phase delay but expressed in different units) as a more accurate measure of high order lag effects. These are shown in Figure 5. (Despite the limitations of the fixed gain mode, the approach and landing qualities were still very satisfactory).

Some interpretation is necessary in the meaning of the gain limits, as it can be the case that a response might be classed as Level 2 by its phase rate and frequency, but as Level 1 or Level 3 by the gain criterion. The author would interpret the gain as signifying better or worse PIO characteristics, so that any oscillation would be unlikely to diverge with a Level 1 gain but would probably be divergent with a Level 3 gain. The response should still be classed as Level 2 in the first case but must be downgraded to Level 3 in the second case.

The author's adoption of "Level" boundaries in design criteria carries no official status, but reflects only his own analysis of the experimental data based on pilot comments and ratings according to the "Level" concept.

Applicability of Figure 5

The criteria boundaries represent an analysis of a range of response dynamics that is relatively small compared with the numbers of PIO events that have actually occurred. Many of the configurations were flown only once by only one pilot, and the opinion rating attached to it might not be repeated exactly by other pilots. Other configurations might have led eventually to a PIO given enough exposure to more pilots and more difficult flight conditions. There is a considerable "grey area" in deciding whether an oscillation should be called a PIO or pilot over-control resulting from unfamiliarity or insufficient adaptation. It is unlikely that exact boundaries of Level 1, Level 2 and Level 3 PIO qualities could ever be precisely delineated for all examples of high order PIO.

With three different parameters to be assessed, one of them potentially requiring some interpretation, it cannot be claimed that this criteria set is guaranteed to quantify with absolute accuracy the pilot rating of the PIO tendencies of past configurations. What is certain is that the further outside the Level 1 limit boundaries that the response of a new design penetrates, the worse its PIO tendencies will be. On the other hand, responses just within the Level 1 limits in all respects are unlikely to experience significant high order PIO, but they still possess undesirable residual high order characteristics. The classical aircraft of old without power control actuation would plot far out of sight to the right on the bottom edge of the phase rate figure, with a response gain equally far out of sight downwards on the gain plot. Between this ideal extreme and the practical reality lies a range of increasing high order effects that will eventually lead to PIO tendencies. Except for unavoidable actuation dynamics, these effects are entirely artefacts of, and therefore under the control of, the control law designer.

It will be recalled that the definition of Level 1 includes the Cooper-Harper 3 pilot rating with "some mildly unpleasant deficiencies". A good designer should not simply be content to obtain the minimum standard just within the Level 1 limits. The designer should set handling qualities aims equivalent to CHR 2, or better still, CHR 1 which is "*excellent, highly desirable*". The concept of an optimum design aim for handling qualities designated Level 1* (Level 1 star) was used in the EAP control law design guidelines. By illustrating factors that have been associated with PIO ranging from severe to mild or none at all, the Figure 5 criteria point to the response dynamics to be avoided by the maximum possible margin to ensure the absence of PIO.

The following Level 1* limits were recommended for linear response design:

- Maximum average phase rate of 50 deg/Hz, equal to a phase delay of 0.07 seconds.
- Minimum attitude PIO frequency of 1.0 Hz.
- Maximum attitude to stick force gain of -20 dB or 0.1 deg/lb at the PIO frequency.
- Maximum attitude acceleration lag of 0.18 seconds in the time response.

(These numbers apply for typical combat aircraft and control inceptors. For other types such as transport aircraft, similar principles but different numbers may be expected.)

Figure 6 revisits the Tornado configurations, which were rectified without benefit of any proven criteria, to compare them with the final version in Figure 5. It supports the author's inference that the first and second pre-filter configurations were not sufficiently different dynamically. The reliance placed at the time on improving the PIO gain value as a major factor in the solution is confirmed by the gain criterion which correctly indicates their relative handling. Although the production version did resolve the PIO problem, it would not pass the later design processes which led to Level 1* anti-PIO qualities in the EAP for example.

Figure 7 compares the stick pumping at touchdown of the Tornado second pre-filter version in the incipient PIO incident and the EAP on an early flight touchdown. The sloppy, low frequency and

large amplitude pumping of the Tornado with about ± 10 lbs of stick force and ± 1 inches of stick input compares dramatically with the classically rapid, small amplitude pumping of the EAP with about 2 lbs of stick force and \pm inch stick input, both cases close to the expected frequencies and producing slightly more than the Bihrlé value of pitch acceleration. The high degree of control that can be exercised by designers over this crucial area of pilot activity is thus clearly demonstrated.

Accounting for actuator saturation

Although the Tornado landing PIO diverged into the non-linear regime of actuator rate limiting, it was resolved by linear control law modifications. During later development of the "bolt on" incidence limiting system, actuator non-linearity became a major issue. Linear analysis in the design stage showed some acceptable reduction in phase margins from the healthy 55 degrees of the CSAS, and simulation, non-linear modelling and rig tests cleared the system for flight. After some 40 flights, a very large amplitude self-sustaining oscillation occurred at about 300 knots.

A quasi-linear actuator response model was derived from matching rig tests. Figure 8 shows the very rapid loss of phase once full rate saturation commenced, typical of acceleration limiting (Reference 6). This was used to calculate the aircraft attitude dynamics shown in Figure 8. The dominant feature is the "explosive" growth in the PIO gain as the control inputs become larger. As the actuator demand doubles from ± 7.5 degrees of tailplane to ± 15 degrees, the amplitude ratio quadruples giving eight times the response for twice the stick input. A new non-linear model of the actuator was also developed with an excellent match to the rig results for all demand amplitudes. With this model the event could be replicated exactly by analysis. This enabled the correct design modifications to be developed which effectively linearised the large amplitude response dynamics, not merely by reducing the phase lag due to rate saturation but by virtually preventing the occurrence of the saturation altogether.

The most significant factor was found to be the actuator acceleration limiting. The oscillation event could not be replicated analytically using only the actuator rate limit. This is not usually discussed in the literature, but it is obvious that the pure saw-tooth waveform often presented as actuator rate limiting cannot occur in practice. The finite time it takes for the main control valve to be moved from one end to the other of its stroke represents the acceleration limit. The Tornado tail actuator control valves were driven by an integrated quadruplex actuator, and though fast it adversely affected the saturated large amplitude response dynamics. While most fly by wire actuators have servo drives with much higher bandwidth and rate, the effect of the acceleration limit is always present and must be included in the actuator modelling for any serious design analysis of large amplitude PIO resistance.

However, the best means of preventing problems is to provide sufficiently high rates and to ensure that the forward path command gain at higher frequencies is not unnecessarily large. If the linear design is also sufficiently low order-like, then the dynamics at the PIO frequency may change gradually as the input amplitude increases but will not show any sudden and large changes to trigger a PIO.

Ideally, the rates would be chosen to ensure that the actuation remains unsaturated at frequencies up to the PIO value using the maximum possible pilot inceptor amplitude. The use of design inputs smaller than this ignores PIO history. Unfortunately the rates will probably need to be chosen before the control law design is sufficiently developed to ensure this at critical flight conditions. A rate sufficient to reach full deflection from neutral in 0.2 seconds permits a full cycle of maximum amplitude oscillatory control travel while fully rate saturated in 0.8 seconds (i.e. 1.25 Hz) if there is no serious acceleration limiting. It is hard to imagine that this would not be sufficient when coupled with proper demand attenuation at PIO frequencies. For lower rates this attenuation can be adjusted to suit.

The choice of desirable maximum rates can be confused by misunderstanding the implication of the units of rate. High numbers tend to alarm management. The important parameter is how long it takes for a control to be applied. If a minimum time of 0.2 seconds is desired, the corresponding rate for roll control by a differential tailplane system of ± 5 degrees authority is 25 deg/sec (although this would be inadequate for the tailplane's symmetrical pitch control function with perhaps a total travel of ± 15 degrees). For a spoiler system with 50 degrees deflection, the equivalent rate is 250 deg/sec. Allowing for the differing control surface sizes and hinge moments, the hydraulic power requirements would be roughly similar despite the 10 to 1 range of angular rates. It is important to get over the message that high rate capability does not mean that pilots will sit there thrashing the controls at maximum rate for long periods, therefore requiring large hydraulic power and flow capability. It is only necessary to provide sufficient accumulator capacity to allow one or two large transient inputs followed by a short dwell in which time the accumulator can be recharged. It is lack of transient rate capability that can lead a pilot into a saturated PIO.

Such a provision has been made on the Jaguar FBW, EAP and Eurofighter with actuator rates of up to 100 degrees per second. Because of their high instability levels, these aircraft could not tolerate significant rate saturation in the pitch controls. The rudder control rate was also critical, since its heavy usage to minimise sideslip in providing "feet off" co-ordinated rolling can require high rates to prevent loss of control in carefree gross combat manoeuvres involving full pitch and roll inputs in any combination including simultaneously. A second line of defence is to place software rate limits of a lesser value on the actuator inputs, e.g. 80 degrees per second, so that the actuators never reach a hard limit. A third defence is to place software rate limits on the inceptor output signals so that the actuator input rate limits are not invoked or at least are invoked only very briefly. Inceptor signal rate limiting, being series or open loop, has been found to be tolerated more readily than closed loop saturation at the actuators. None of these aircraft has shown the slightest tendency to Type 2 or Type 3 saturation effects in flight.

Designing and testing for good handling

While the thrust of this paper has been the prevention of safety-related PIO, it goes without saying that the provision of good handling qualities is a necessary precursor. This includes the prevention of pitch oversensitivity and non-safety-related "low order" PIO such as pitch bobble or the "PIO syndrome" effect due to excessive attitude dropback or an excessive Bode plot shelf width. These can easily be dealt with by use of the methodologies described in Reference 3, for example. Again the designer should aim for "Level 1*" qualities, so that inevitable shortfalls in some areas will still provide Level 1 handling. Generally this aim can be achieved by a K/s-like behaviour below the bandwidth frequency, but this must be applied to the appropriate response.

Although control of an aircraft invokes both attitude and flight path, excellent results have been obtained by optimising the attitude and accepting the fall-out flight path response. This can be taken only so far, however. The latter may well acquire non-classical features such as "g creep" and this must always be assessed for acceptability. Flight path control must take precedence in the landing task, for example, where path control PIO is always a possibility even with classical response dynamics. Here it is also possible to apply the desired K/s-like dynamics to the HUD in the form of a quickened climb-dive or velocity vector symbol, giving very precise flight path predictability and touch down control.

Generally, the faster and higher an aircraft flies, the more dominant the control of flight path becomes. More strictly, it is control of angle of attack rather than pitch rate that becomes more important. This is because the steady pitch rate in manoeuvres becomes small relative to the angle of attack required, which takes too long to acquire initially at anything like the steady pitch rate

value. Substantial pitch rate overshoot and attitude dropback ratios then become necessary. An extreme example, discussed (with very approximate data) in Reference 3, is the YF-12 in cruise at Mach 3 or about one kilometre per second, and hence with extremely low pitch rates per g. Figure 9 shows a time response sketch indicating a good K/s-like path response but an attitude dropback ratio of 5 and pitch rate overshoot ratio of 6, which are very large by normal standards.

Although such attitude parameters would be highly unsatisfactory in the majority of normal flight conditions, here their effects are rather insignificant. The normal acceleration increment of about $0.11g$ used to acquire an attitude change of 0.3 degrees for a 1000 foot per minute climb in a height change manoeuvre required a steady pitch rate of only about 0.07 degrees per second. Hence the physical dropback and peak pitch rate were about 0.35 degrees and 0.4 degrees per second. A K/s-like attitude response could be enforced, say by a lag-lead command prefilter, but the result would be an impossibly long hang-off or g creep as shown in the second sketch. Despite excellent attitude control, the flight path angle response is made so sluggish that a slow overdriving PIO would be the most likely outcome of any attempt to acquire a constant altitude or climb angle. Whether this is truly safety-related is not clear, but it would certainly give a supersonic airliner captain a hard time with hand flying.

By the start of pre-flight clearance testing, all traces of serious PIO should have been removed by rigorous design and analysis employing up to maximum amplitude inputs as noted earlier. Even though this may not represent normal realistic control usage (though it is normal for truly carefree handling aircraft, where anything goes), a control system unable to withstand this has not been properly designed. A piloted simulation search for PIO triggers may well be carried out, but failure to find a trigger task may only mean that the right one has not been thought of. A PIO will always occur, eventually, if the response dynamics permit it. PIO cannot occur if it has been designed out of the system, a possibility that has been demonstrated now on several fly by wire aircraft. A fixed base simulation is certainly capable of showing that Type 2 or Type 3 PIO characteristics are not present, provided that the control system dynamics are very accurately modelled from theoretical analysis and rig tests.

After the Tornado, flight testing for PIO at Warton has been confined to a few high pilot gain precision tasks. One was synthetic HUD target tracking, which showed up a small lateral tracking oscillation on the EAP caused by a feature introduced to optimise rapid turn entry co-ordination. On the Jaguar FBW, flight refuelling trials were done at the end of its programme in its most unstable configuration, without specific pre-task tests but with knowledge of excellent formation qualities and absolute confidence by then in its freedom from PIO. Eight dry contacts were made showing very easy control. On Eurofighter, tests of very close formation flying were made behind a Tornado prior to actual contacts with a Victor tanker. The refuelling task was found to be an order of magnitude easier than with previous conventional aircraft, and in fact Cooper/Harper ratings of 1 and 2 were given. Very aggressive pitch tracking has shown an extremely stable tracking platform. Flight testing for safety-related landing PIO has not been seen as either practical or necessary given the intense scrutiny applied to the design and pre-flight testing.

Final comments

To design a control system and only then to test it for PIO is a very high risk strategy. To ensure freedom from PIO, it is essential to plan its absence from the very beginning, starting with a properly constructed and thought out control law layout, maintaining a highly visible block diagram on which all paths can be followed and their effects understood, and considering the impact on possible PIO of the system hardware and of every change to the control laws.

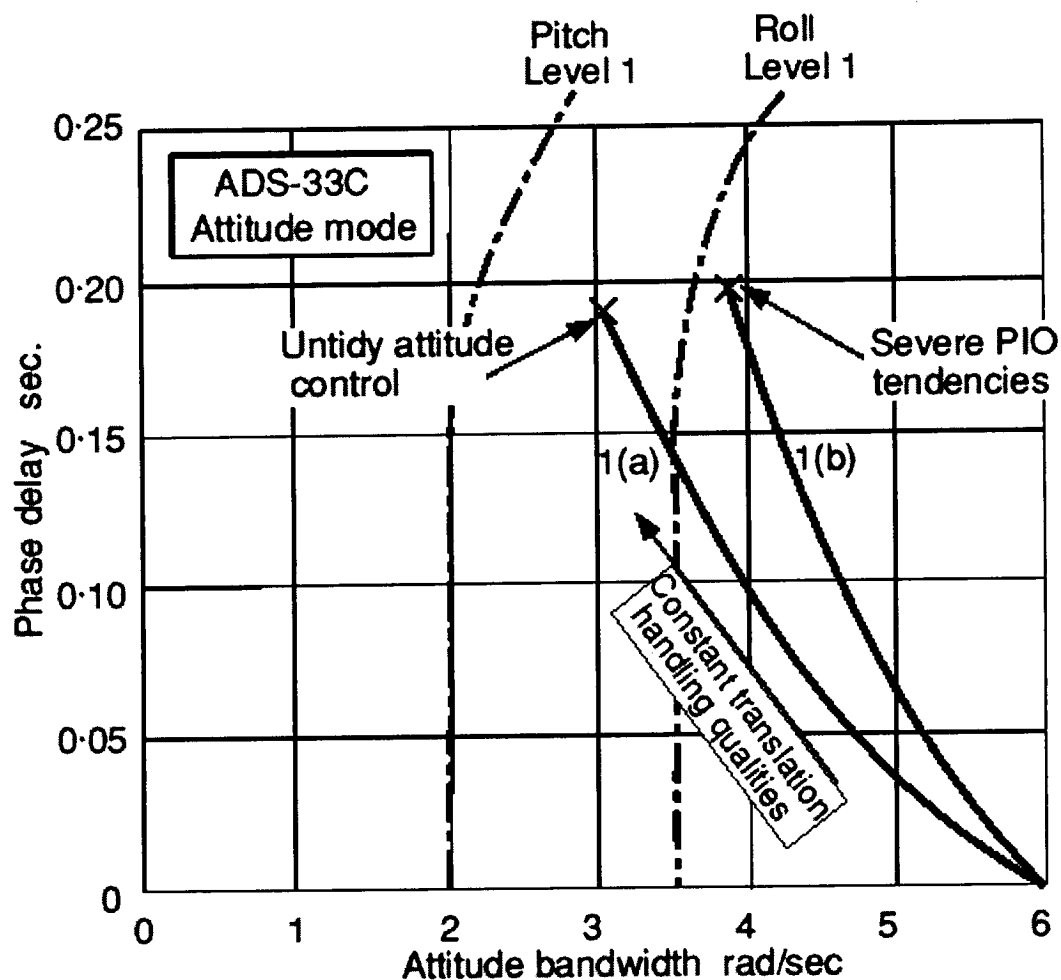
Reference 7, an excellent review of the past PIO problem initiated after the YF-22 PIO in 1992, recommends a change in paradigm from "Proceed unless a PIO problem is proven to exist" to

"Proceed only when resistance to PIO is proven". It will be obvious that this author wholeheartedly concurs.

The essence of safety-related PIO prevention by design is simply stated: the PIO frequency cannot be too high, the PIO gain cannot be too low, the phase delay cannot be too small, and the large amplitude response cannot be linearised too much.

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1(a) has critical damping and low PIO gain, with translation control qualities that remain constant as bandwidth reduces and phase delay increases, while the attitude control becomes untidy.

1(b) has Level 1 damping (0.5), phase delay and bandwidth to ADS-33C, but degrades to dangerous PIO due to high PIO gain and motion coupling as phase delay increases.

Figure 1 Generic ASTOVL research:
Lateral translation handling in roll attitude mode

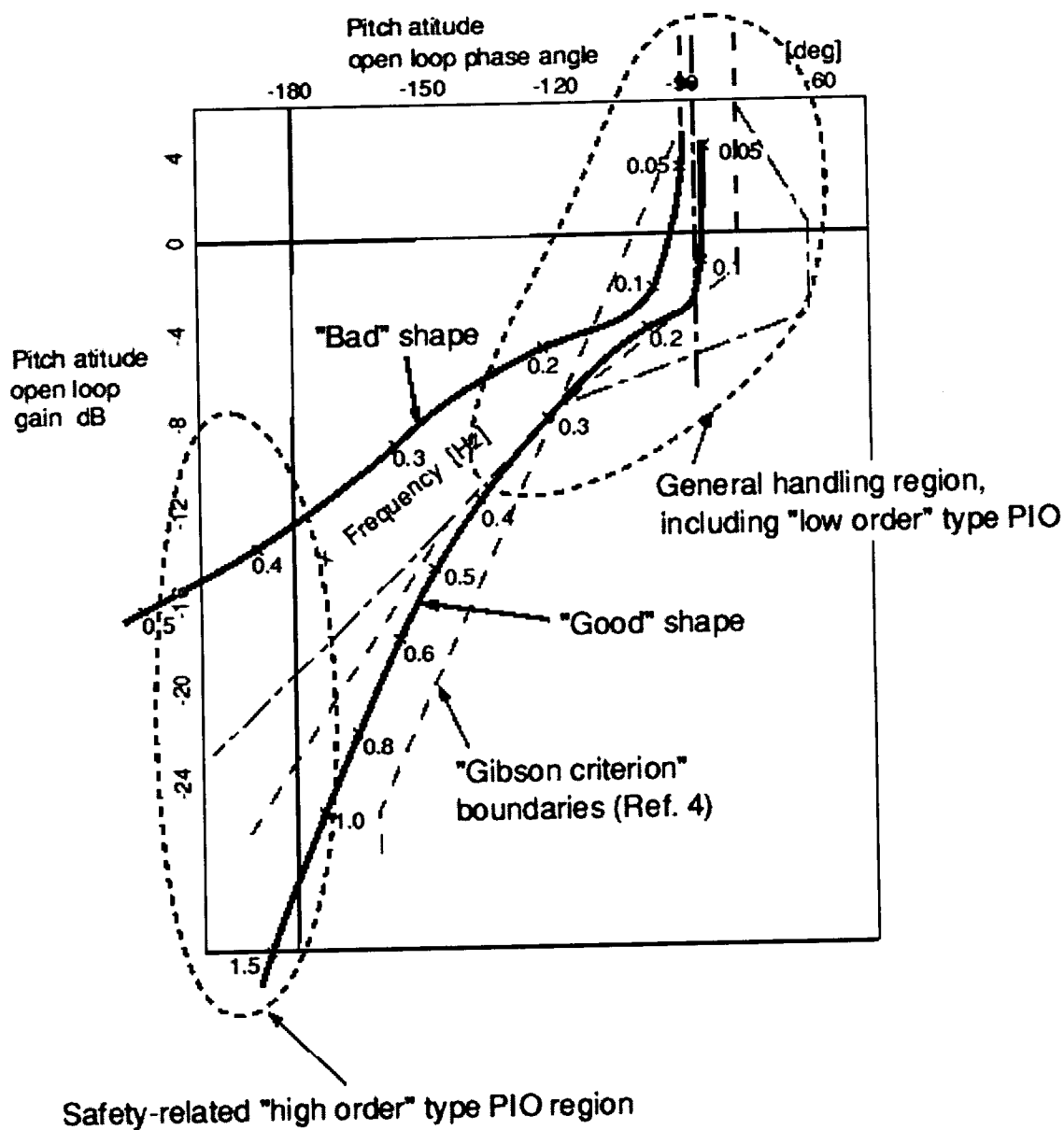
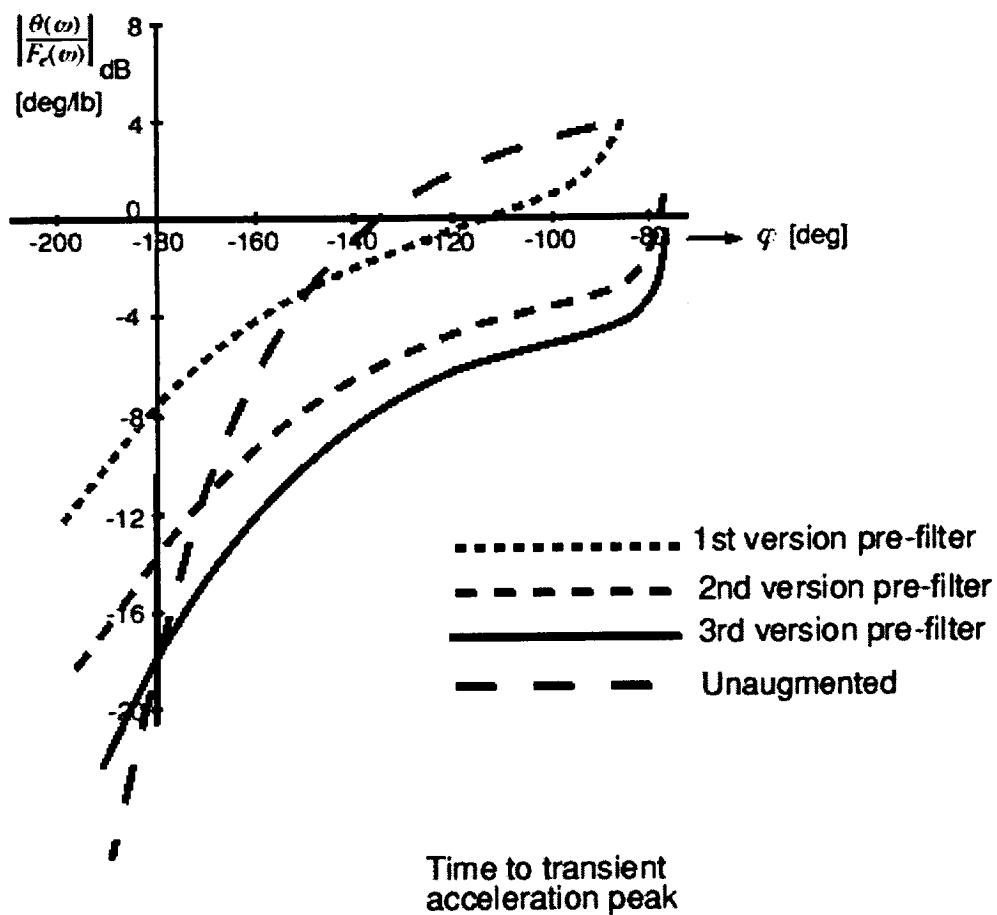


Figure 2 Frequency response qualities illustrated by non-parametric shape



Version	PIO frequency		t_q sec	Pre-filter characteristics
	Bandwidth			
1st	$\omega(-120)$ Hz	$\omega(-180)$ Hz	0.35	$(1 + 0.157s)/(1 + 0.47s)$
2nd	0.245	0.455	0.3	$(1 + 0.133s)/(1 + 0.454s)(1 + 0.0625s)$
3rd	0.26	0.535	0.22	(1.0)
Unaug.	0.145	0.44	0.12	(1.0)

Figure 3 Tornado pitch attitude responses at landing: solution to PIO by development of the command pre-filter.

The unaugmented and third version pre-filtered dynamics are PIO-free.

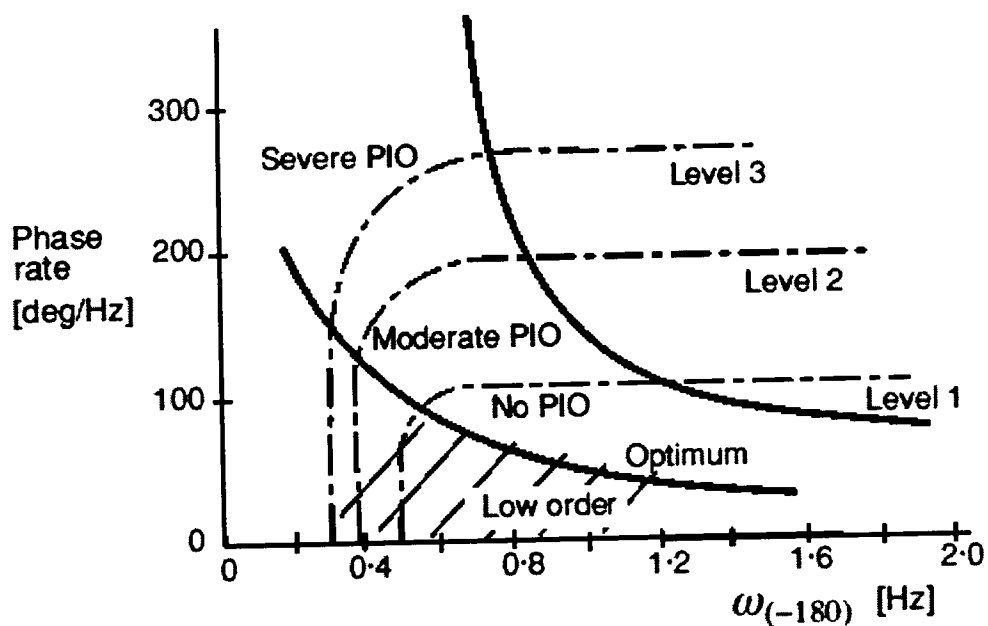
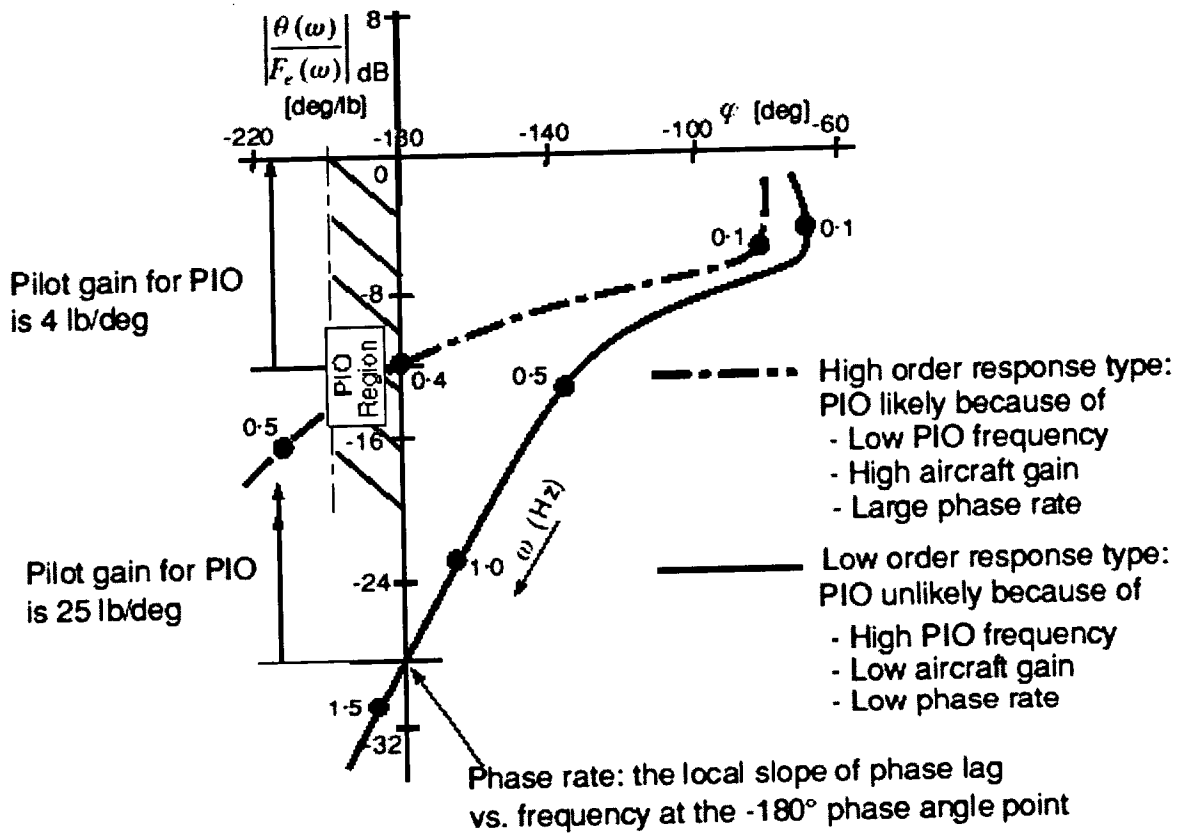
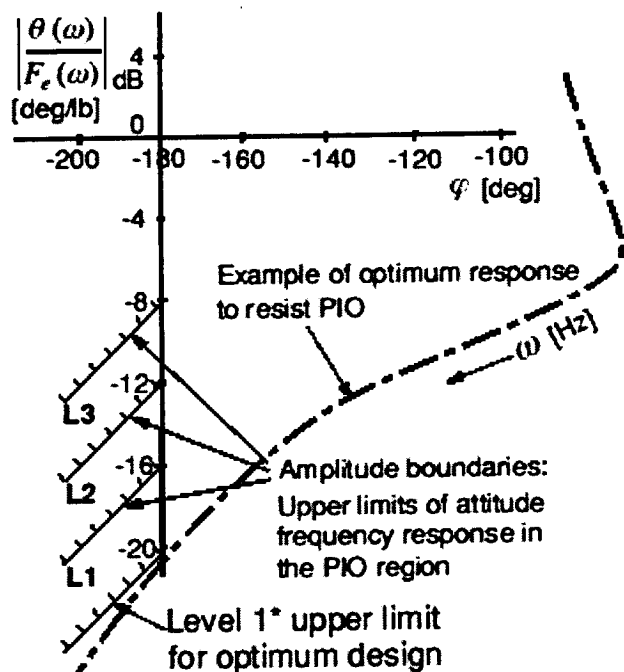
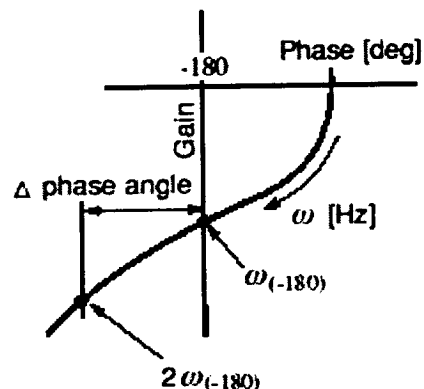


Figure 4 PIO tendency indicators and design guidelines derived from LAHOS etc.

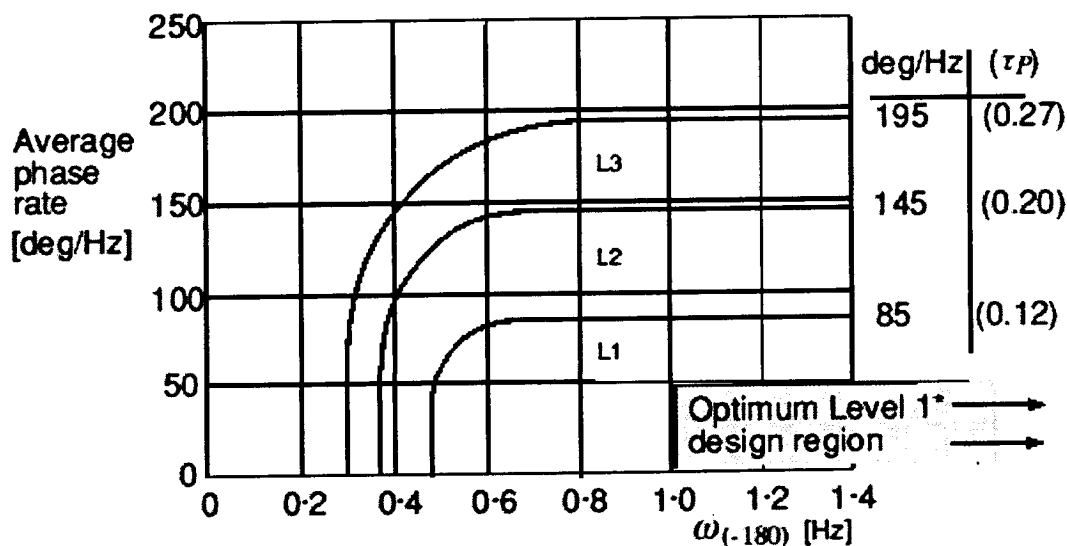


(a) PIO gain limit criterion



Average phase rate
 $= \{-\Delta \text{ phase angle} + \omega_{(-180)}\} \text{ deg/Hz}$
 Phase delay τ_p
 $\equiv \{\text{Average phase rate} + 720\}$

(b) Definition of average phase rate



(c) Phase rate and frequency criterion

Figure 5 Final development of PIO criteria (1993)

1. Level 1, 2 and 3 boundaries represent historical data.
2. Undesirable residual high order characteristics exist within the Level 1 region near the low frequency boundary limit.
3. Best design practice for freedom from linear high order PIO requires the more stringent Level 1* gain, phase rate and frequency limits.

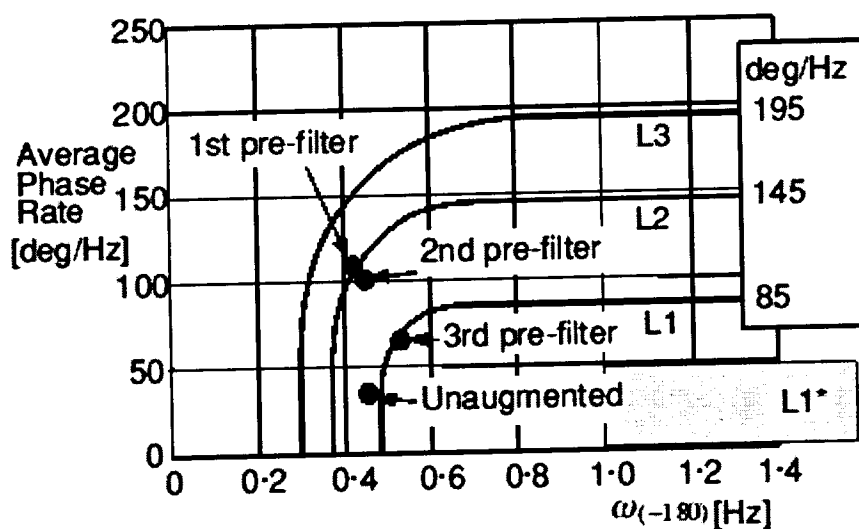
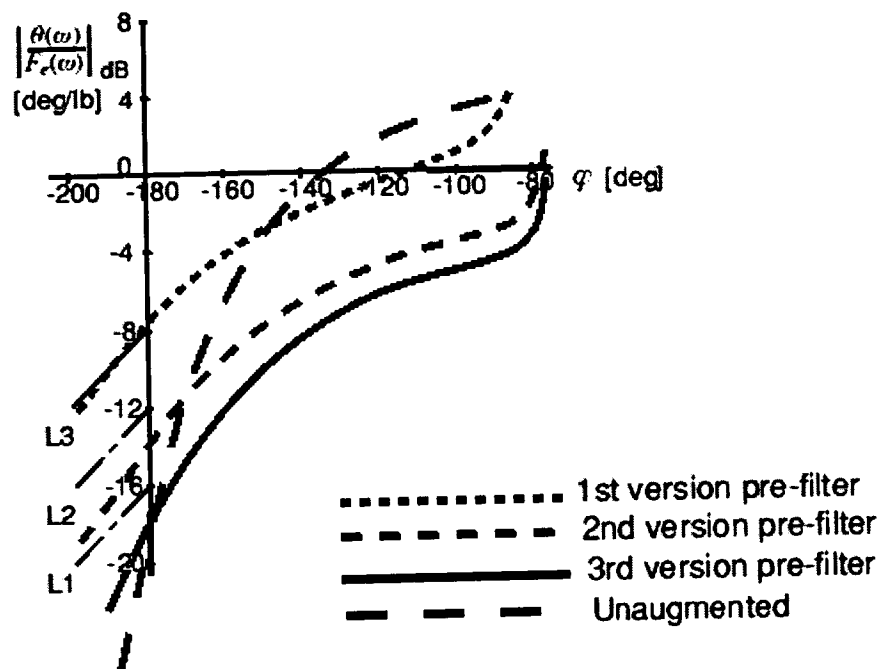


Figure 6 Tornado viewed in retrospect against author's later criteria

Note: although the 3rd pre-filter just satisfies the criterion and has prevented PIO for 20 years, it would not have been accepted as a new design by subsequent criteria.

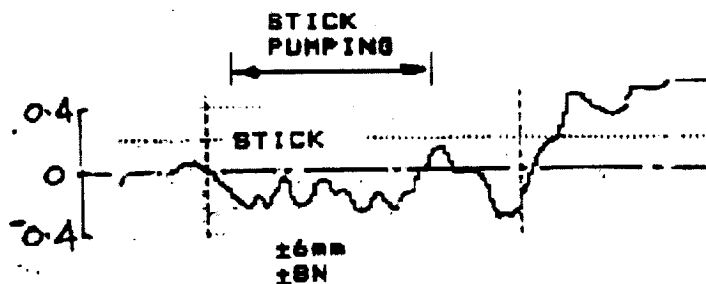
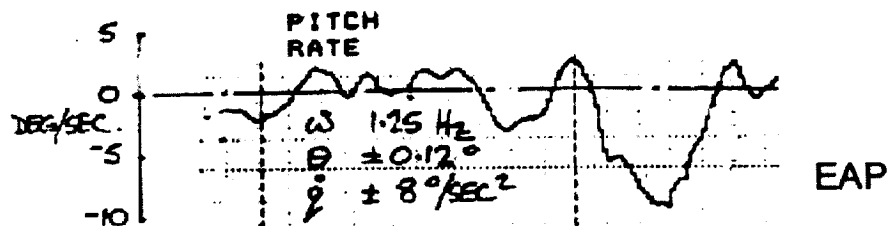
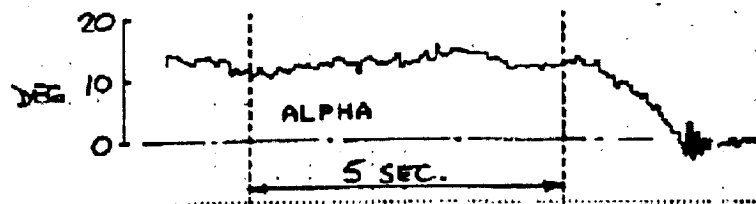
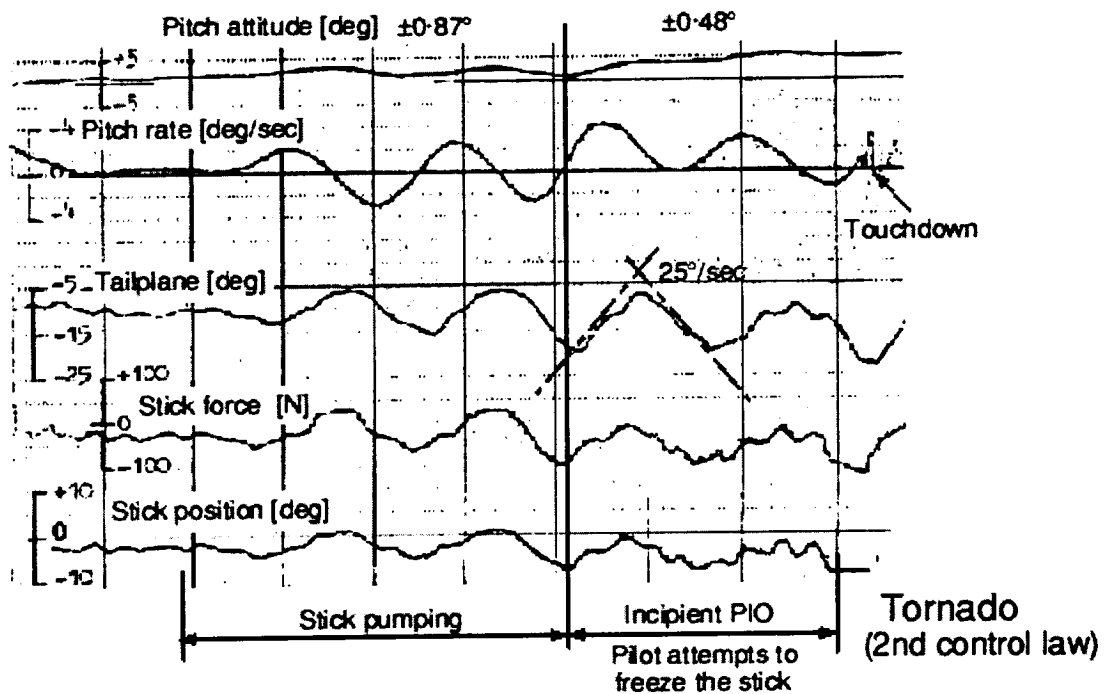


Figure 7 Effect of design process on stick pumping and associated PIO resistance

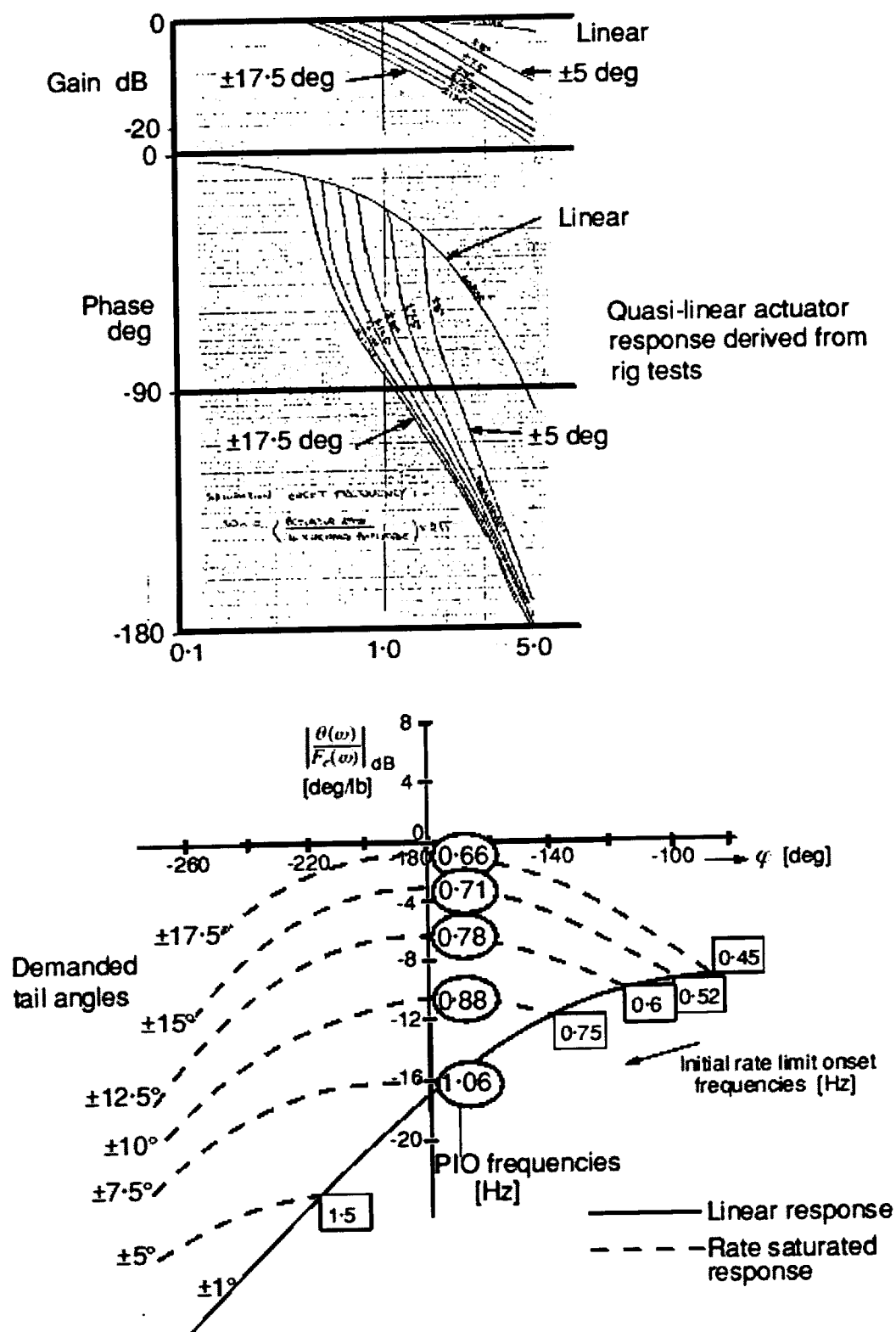
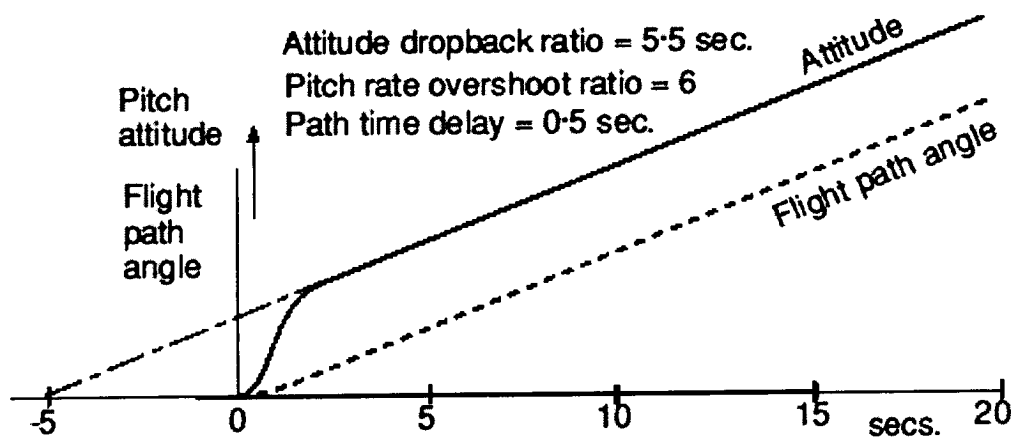
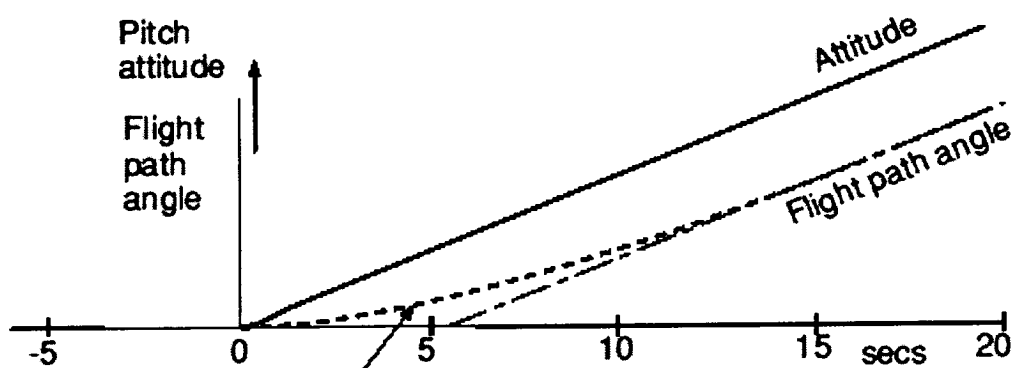


Figure 8 Significant non-linear actuation effects on PIO characteristics



Nominal YF-12 time response
at Mach 3 cruise



Short period roughly approximated by:

$$\omega_{sp} = 0.5 \text{ rad/sec}$$

$$\zeta_{sp} = 1.3$$

Path delay = 5.2 sec.

$$\text{YF-12 with pre-filter} = \frac{1 + 0.8s}{1 + 5.5s}$$

Figure 9 Sluggish PIO-prone flight path response caused by
inappropriate pitch attitude optimisation

PILOT-INDUCED OSCILLATION PREDICTION WITH THREE LEVELS OF SIMULATION MOTION DISPLACEMENT

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Abstract

Simulator motion platform characteristics were examined to determine if the amount of motion affects pilot-induced oscillation (PIO) prediction. Five test pilots evaluated how susceptible 18 different sets of pitch dynamics were to PIOs with three different levels of simulation motion platform displacement: large, small, and none. The pitch dynamics were those of a previous in-flight experiment, some of which elicited PIOs. These in-flight results served as truth data for the simulation. As such, the in-flight experiment was replicated as much as possible. Objective and subjective data were collected and analyzed. With large motion, PIO and handling qualities ratings matched the flight data more closely than did small motion or no motion. Also, regardless of the aircraft dynamics, large motion increased pilot confidence in assigning handling qualities ratings, reduced safety pilot trips, and lowered touchdown velocities. While both large and small motion provided a pitch rate cue of high fidelity, only large motion presented the pilot with a high fidelity vertical acceleration cue.

Notation

a, b, c prefilter zeros and poles, rad/sec
 a_{model} model acceleration, ft/sec², rad/sec²
 a_{motion} motion system commanded acceleration, ft/sec², rad/sec²
 $F(x, y)$ variance ratio with x and y degrees of freedom

$F_{\text{lon}}, F_{\text{lat}}, F_{\text{ped}}$ long., lateral stick and pedal force, lbs
 h_{td} touchdown vertical velocity, ft/sec
 K control system prefilter gain
 K_{mot} motion system filter high-freq gain
 K_{θ} control system gearing, deg/in
 $L_{\delta_{\text{lat}}}$ lateral control sensitivity, 1/sec²/in
 M_{δ_e} elevator control sensitivity, 1/sec²
 $N_{\delta_{\text{lat}}}$ directional control sensitivity, 1/sec²/in
 n number of points in each mean
 p probability that effects are random
 s Laplace transform variable, rad/sec
 $T_{\theta_1}, T_{\theta_2}$ pitch-to-elevator zero time constants, sec
 β sideslip angle, deg
 δ_e elevator deflection, deg
 δ_{ec} commanded elevator, deg
 $\delta_{ec\text{filt}}$ filtered commanded elevator, deg
 δ_{estick} commanded elevator from stick, deg
 $\delta_{\text{lon}}, \delta_{\text{lat}}, \delta_{\text{ped}}$ longitudinal, lateral stick and pedal deflection, in
 ζ_{dr} Dutch roll damping ratio
 ζ_{mot} motion filter damping ratio
 $\zeta_{\text{sp}}, \zeta_{\text{sp}}$ phugoid and short period damping ratio
 ζ_1, ζ_2 control system prefilter damping ratios
 ζ_{ϕ} complex zero damping ratio in bank-to-aileron transfer function
 θ, ϕ pitch and roll angles, deg
 τ_r, τ_s roll and spiral mode time constants, sec
 ω_{dr} Dutch roll natural frequency, rad/sec
 ω_{mot} motion system filter natural frequency rad/sec
 $\omega_p, \omega_{\text{sp}}$ phugoid and short period natural fr rad/sec

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† Aerospace Engineer. Member AIAA.

ω_1, ω_2 control system prefilter natural frequencies, rad/sec
 ω_ϕ complex zero natural freq. in bank-to-aileron transfer function, rad/sec

Introduction

Ground simulation has not been very successful at predicting subsequent in-flight pilot-induced oscillations (PIOs). A recent study recommended that "validating simulation details, protocols, and tasks and collecting and correlating them with flight test results should be given high priority" to improve this simulation weakness.¹

With two fixed-base simulators of different capabilities, Ref. 2 evaluated the longitudinal PIO tendencies of configurations tested in a PIO flight test study.³ The simulation results followed the general trend of the in-flight data; however, the worst in-flight configurations were not as severe on either fixed-base simulator.

The purpose of this study was to determine what effect simulator platform motion has on predicting PIOs. Here, three simulator platform motion characteristics were examined: large, small, and no motion. Five pilots flew a landing task with 18 different sets of longitudinal dynamics with each motion configuration. Both pilot-vehicle performance and subjective data were taken and compared with the previous in-flight study.³

Apparatus and Tests

Task

The in-flight task was replicated as much as possible.³ Pilots started at 135 knots and 1.5 nmi from the runway and flew three visual approaches to full touchdown with each configuration. One approach was straight-in, and one each started with a 150-ft left or right lateral offset from the touchdown point. During the approach, pilots were instructed to maintain constant speed and remain on the glidepath (-2.5 degs) and localizer. Deviations were indicated on head-down instruments. At the start of the run, the aircraft was placed 1/2 dot off the desired localizer and glideslope.

For the left and right offsets, pilots held that offset until an automated voice instructed the pilot to "correct." The pilot then maneuvered the aircraft to land on the desired touchdown point. The "correct" command occurred when the runway overrun disappeared

from the visual field-of-view, which corresponded to an altitude of 100 ft.

Figure 1 shows the desired touchdown point, which was the near-left corner of the 1000-ft fixed distance marker located to the right of centerline. This desired touchdown point matched the flight-test study. Table 1 gives the performance standards for the task.

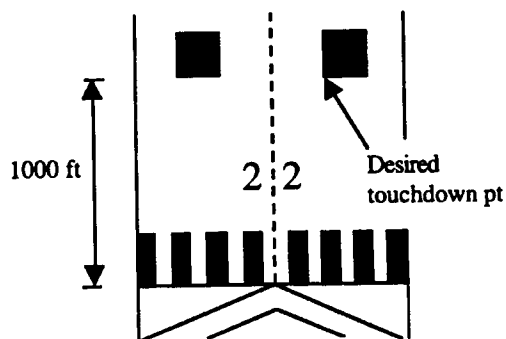


Figure 1 - Landing task

Table 1 - Task performance standards

	Desired	Adequate
PIOs	None	None
Longitudinal touchdown error	+/- 250 ft	+/- 500 ft
Lateral touchdown error	+/- 5 ft	+/- 25 ft
Approach airspeed	+/- 5 kts	-5/+10 kts

Math model

Longitudinal configurations. A linear stability derivative model⁴ generated the aerodynamic forces and moments on the aircraft. Bare airframe derivatives were combined from several sources.^{3,5,6} Response feedbacks of angle-of-attack and pitch rate to the elevator were used to simulate the different pitch configurations, given below, which mimics the NT-33 variable stability aircraft.⁵ Figure 2 shows the dynamic blocks of the pitch axis dynamics.

The simulation centerstick dynamics were measured as:

$$\frac{\delta_{lon}}{F_{lon}}(s) = \frac{0.125(22^2)}{s^2 + 2(0.7)(22)s + 22^2}$$

These dynamics are slower than the 25 rad/sec stick longitudinal natural frequency stated in Refs. 3 and 7 due to force-feel system limitations of this simulator cockpit. The ergonomics of the stick matched Ref. 7.

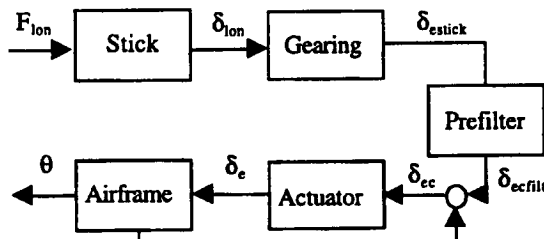


Figure 2 - Longitudinal block diagram

Fourteen prefilters were simulated as in the in-flight experiment. These prefilters consisted of first, second, and fourth-order linear filters. These filters are of the form below, and Table 2 gives their values:

$$\frac{\delta_{e_{cfilt}}}{\delta_{e_{stick}}}(s) = \frac{K(s+a)}{s+b}$$

$$\frac{\delta_{e_{cfilt}}}{\delta_{e_{stick}}}(s) = \frac{K}{s+c}$$

$$\frac{\delta_{e_{cfilt}}}{\delta_{e_{stick}}}(s) = \frac{K}{s^2 + 2\zeta_1\omega_1s + \omega_1^2}$$

$$\frac{\delta_{e_{cfilt}}}{\delta_{e_{stick}}}(s) = \frac{K}{(s^2 + 2\zeta_1\omega_1s + \omega_1^2)(s^2 + 2\zeta_2\omega_2s + \omega_2^2)}$$

Table 2 - Control system prefilters

Filter	K	a	b	c	ζ_1	ω_1	ζ_2	ω_2
B	3.0	3.3	10	-	-	-	-	-
D	0.5	20	10	-	-	-	-	-
1	1.0	-	-	-	-	-	-	-
2	10	-	-	10	-	-	-	-
3	4.0	-	-	4	-	-	-	-
5	1.0	-	-	1	-	-	-	-
6	16 ²	-	-	-	0.7	16	-	-
7	12 ²	-	-	-	0.7	12	-	-
8	9 ²	-	-	-	0.7	9	-	-
9	6 ²	-	-	-	0.7	6	-	-
10	4 ²	-	-	-	0.7	4	-	-
11	16 ⁴	-	-	-	0.93	16	0.38	16
12	2 ²	-	-	-	0.7	2	-	-
13	3 ²	-	-	-	0.7	3	-	-

Commanded elevator deflection was the sum of the prefilter output and the feedbacks of angle-of-attack and pitch rate. The elevator actuator dynamics were modeled as a second-order filter with the NT-33 rate and position limits.⁷ In the linear range, the actuator dynamics are:

$$\frac{\delta_e}{\delta_{e_c}}(s) = \frac{75^2}{s^2 + 2(0.7)(75)s + 75^2}$$

Four sets of aircraft dynamics were evaluated. The differences among the dynamics were effectively in the short-period mode. The pitch-to-elevator transfer function had the following form:

$$\frac{\theta}{\delta_e}(s) = \frac{M\delta_e(s+1/T_{\theta_1})(s+1/T_{\theta_2})}{(s^2 + 2\zeta_p\omega_p s + \omega_p^2)(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

Table 3 gives the parameters for the above transfer function. For all configurations, $M_{\delta_e} = -3.3$ 1/sec².

Table 3 - Aircraft dynamics

A/C	T_{θ_1}	T_{θ_2}	ζ_p	ω_p	ζ_{sp}	ω_{sp}
2	12	1.4	0.15	0.17	0.64	2.4
3	12	1.4	0.17	0.16	1.0	4.1
4	12	1.4	0.16	0.16	0.74	3.0
5	12	1.4	0.16	0.15	0.68	1.7

The remaining parameter to be specified is the gearing between the elevator command from the stick and the longitudinal stick position. For the 18 tested configurations, which represent combinations of the aircraft dynamics and prefilters, the gearings are listed in Table 4. As an example, for configuration 2-B, the "2" corresponds to the values in Table 3 and the "B" corresponds to the values in Table 2.

Subsequent to the experiment's start, information from the Ref. 2 authors indicated that the Table 4 gearings may have been 70% higher than in the flight test. To evaluate the effect of different gearings on the results, a mini-experiment was run using the Ref. 2 gearings with configurations 3-1, 3-D, and 3-12. Differences between gearings were less than or equal to one handling qualities and pilot-induced oscillation point.

Each of the 18 configurations was verified by performing frequency sweeps on each and overplotting the result against the analytical pitch-rate-to-stick-deflection transfer functions.

Table 4 - Gearings			
Config	K_θ	Config	K_θ
2-B	-2.94	3-8	-7.29
2-1	-2.94	3-12	-7.29
2-5	-4.33	3-13	-7.29
2-7	-2.94	4-1	-3.46
2-8	-2.94	4-2	-3.46
3-D	-8.65	5-1	-1.73
3-1	-7.29	5-9	-1.73
3-3	-7.29	5-10	-1.73
3-6	-7.29	5-11	-1.73

The engine model consisted of a first-order transfer function from throttle input to thrust output. The time constant was nonlinear and depended on RPM.⁷

Lateral. Using a lateral-directional stability derivative model, coefficients were adjusted to achieve the following modal and sensitivity characteristics:

$$\begin{aligned}\tau_r &= 0.3 \text{ sec} \\ \tau_s &= 75 \text{ sec} \\ \omega_{dr} &= \omega_\phi = 1.3 \text{ rad/sec} \\ \zeta_{dr} &= \zeta_\phi = 0.2 \\ \left| \frac{\phi}{\beta} \right|_{dr} &= 1.5 \\ L_{\delta_{lat}} &= 0.7 \text{ rad/sec}^2/\text{in} \\ N_{\delta_{ped}} &= -0.2 \text{ rad/sec}^2/\text{in}\end{aligned}$$

These characteristics were also verified with frequency sweeps.

Atmosphere. Dryden turbulence with rms magnitudes of 3 ft/sec was used. A vertical 1-cosine gust occurred when the aircraft reached an altitude of 100 ft. The gust had a peak of 12 ft/sec and was time scaled based on the 6.7 ft chord of the NT-33.

Safety pilot. Evaluation pilots in the NT-33 flight study were accompanied by a safety pilot, who ended the evaluation and assumed control of the aircraft if a potentially hazardous situation occurred. If a safety pilot assumes control, then questions arise immediately on that configuration's "controllability" from the handling qualities point of view. The presence of a safety pilot can also add a factor of stress, since another set of eyes is watching the evaluation pilot.

In this simulation, an automatic safety pilot was implemented that assumed control of the simulated model when the nosewheel's vertical speed exceeded -8 ft/sec below a center-of-mass height of 12 feet. This

criterion was developed empirically and was well received by the pilots. Upon activation, the pilot's controls went dead, a voice said "my airplane," and the math model initiated a go-around.

Simulator

Motion system. The NASA Ames Vertical Motion Simulator (VMS) was used.⁸ It is the world's largest-displacement flight simulator, with capabilities shown in Figure 3. The cockpit was oriented for large longitudinal travel. The dynamics of the motion system were measured during the experiment using frequency response testing techniques.⁹ These dynamics were fit with an equivalent time delay in each axis. Software feedforward filters were used to tune the delays to achieve a close match among axes. The equivalent time delays for the surge, sway, pitch, roll, and yaw axes were all 80 msec, and the heave axis had 110 msec of delay. By comparison, delays in the NT-33 model following control system have been suggested as being in the 45-60 msec range.

VMS Nominal operational motion limits			
Axis	Displ	Velocity	Accel
Vertical	± 30	16	24
Longitudinal	± 20	8	16
Lateral	± 4	4	10
Roll	± 18	40	115
Pitch	± 18	40	115
Yaw	± 24	46	115
All numbers, units ft, deg, sec			

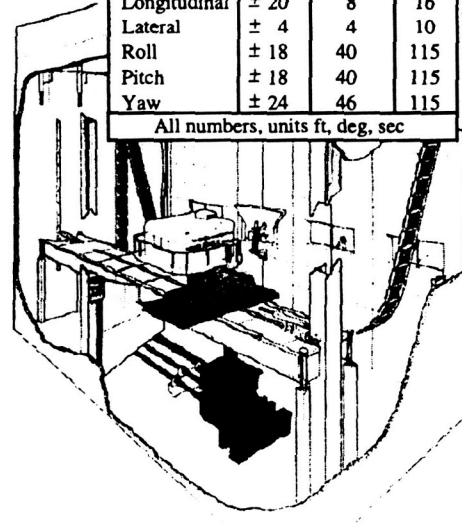


Figure 3 - NASA Ames Vertical Motion Simulator

Visual system. The visual scene was rendered with an Evans & Sutherland ESIG-3000 image generator. Three monitors comprised the field of view, as shown

in Fig. 4. The visual system had a measured time delay of 80 msec from the pilot's stick position to the visual scene. Figure 5 shows the visual scene with the aircraft near the runway. The nose of the simulated aircraft is at the bottom of the field-of-view. Window mullions were added (oval in Figure 5) to replicate the cockpit.⁷

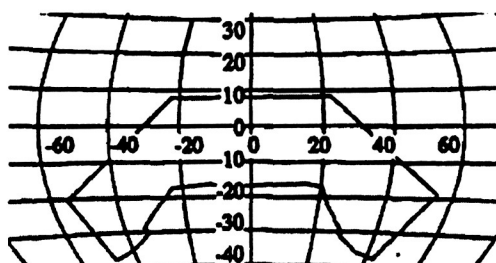


Figure 4 - Cockpit field-of-view

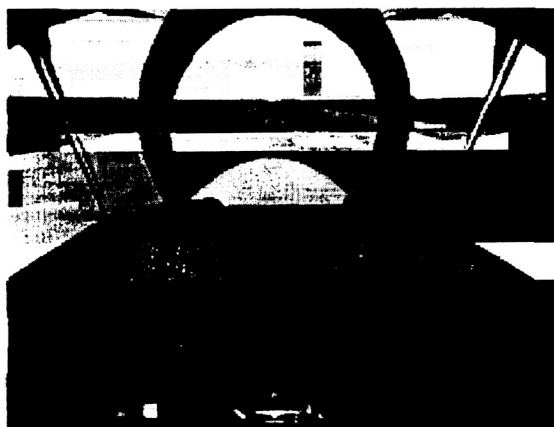


Figure 5 - Simulator cockpit photo

Cockpit. The lateral stick and pedal dynamics were measured as:

$$\frac{\delta_{lat}}{F_{lat}}(s) = \frac{0.25(16^2)}{s^2 + 2(0.7)(16)s + 16^2}$$

$$\frac{\delta_{ped}}{F_{ped}}(s) = \frac{0.0167(25^2)}{s^2 + 2(0.7)(25)s + 25^2}$$

A head-up display was video mixed with the visual scene. The display included a pitch ladder, altitude above sea level, airspeed, rate-of-climb, heading, range, and a flightpath marker. The flightpath marker represented center-of-mass flightpath and used raw data only.

Motion configurations

Three motion configurations were examined: large, small, and no motion. The VMS motion platform software was modified to implement each.

Large motion. The classical washout motion control laws of the VMS were used for this configuration. Second-order high-pass (washout) filters exist between the math model accelerations and the commanded motion system accelerations. These filters have the form:

$$\frac{a_{motion}}{a_{model}}(s) = \frac{K_{mot}s^2}{s^2 + 2\zeta_{mot}\omega_{mot}s + \omega_{mot}^2}$$

In each of the six motion degrees-of-freedom, both K_{mot} and ω_{mot} were adjusted to keep the motion system within its displacement limits using motion system fidelity criteria suggested initially by Sinacori¹⁰ and revised and validated subsequently.¹¹ Table 5 shows the values used. The damping ratio, ζ_{mot} , was 0.7. In addition to these cues, roll/sway coordination and residual tilt crossfeeds were present in the motion logic.¹²

Table 5 - Large motion system parameters

Axis	K_{mot}	ω_{mot}
Pitch	1.00	0.20
Roll	0.40	0.50
Yaw	0.65	0.20
Longitudinal	0.65	0.40
Lateral	0.50	0.50
Vertical	0.80	0.30

Small motion. A coordinated-adaptive algorithm, used on many of today's hexapods, was employed in the small motion configuration.^{13,14} This algorithm assumed a mathematical model of a hexapod platform with 60-in stroke actuators. Thus, the stroke limiting that occurs when commanding several axes was present. Euler angles and translational positions of the platform were back solved on line from the resulting (and potentially limited) actuator positions.¹⁵ The Euler angles and positions were then used to drive the VMS platform.

Second-order high-pass filters were used in the translational axes, while the rotational axes used a first-order high-pass filter (unlike the Large motion configuration). The second-order filters had a damping ratio of 0.7, except for the surge axis, which was 0.8. For comparison, Table 6 gives the gains and natural

frequencies (or pole locations) for the small motion filters. The gains listed are the maximum values, as the coordinated-adaptive algorithm reduces these values when the actuators near their travel limits. These gains were adjusted to use as much of the 60-in actuator stroke as possible.

Table 6 – Small motion system parameters

Axis	K_{mot}	ω_{mot} (or pole)
Pitch	0.50	0.30 (pole)
Roll	0.25	0.81 (pole)
Yaw	0.70	0.30 (pole)
Longitudinal	0.11	0.67
Lateral	0.45	0.90
Vertical	0.13	0.90

No motion. The motion system was turned off in this configuration.

Comparison with fidelity criteria. Figure 6 plots each axis of the large and small motion configurations against the validated criteria of Ref. 11. These points are determined by finding the magnitude and phase of the respective motion filter evaluated at 1 rad/sec.

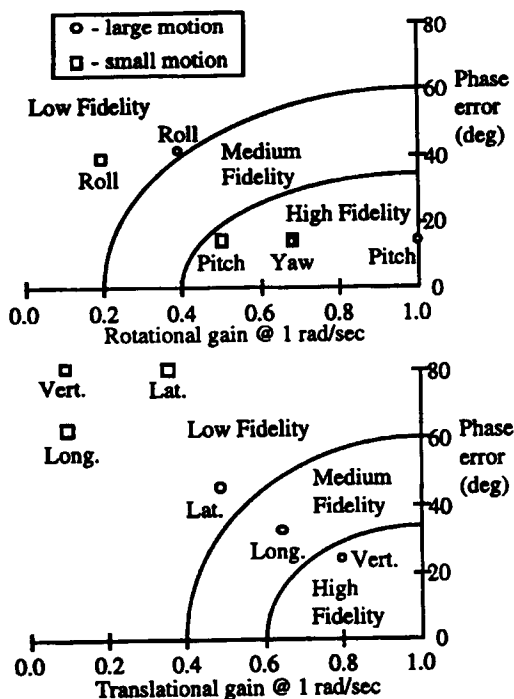


Figure 6 – Motion fidelity prediction

In the rotational axes, high motion fidelity is predicted for both pitch and yaw motion with the large and small motion configuration. Roll motion is low fidelity in both motion configurations, since the roll axis was attenuated to minimize the false lateral specific force cueing during coordinated rolling maneuvers.

In the translational axes, all of the small motion cues are predicted to be low fidelity. For large motion, the fidelity improves, especially for the vertical axis, which provides a key cue for this task. This figure shows the benefit of large motion in fidelity terms.

Pilots

Five experience test pilots, hereafter referred to as A-E, participated. Pilot A was an FAA test pilot, pilots B-D were NASA Ames test pilots, and pilot E was a Boeing test pilot.

Experimental procedure

Summarizing the experimental variables, they were:

1. motion configuration (3),
2. aircraft configuration (18)

Thus, each pilot evaluated 54 configurations. Pilots A, B, and E evaluated each configuration at least twice. Pilots C and D evaluated each configuration only once.

The pilots each read the same experimental briefing. They had no knowledge of the configurations, which were randomized. After flying the task, the pilots were told of their performance. Then, they assigned a handling qualities rating using the Cooper-Harper scale,¹⁶ a Pilot Confidence Factor,¹⁶ and a Pilot Induced Oscillation Rating (PIOR).⁶

Results and Discussion

Objective data

Example PIO. Figure 7 illustrates a classic divergent PIO that occurred with Pilot B, configuration 3-12, and large motion. The pilot was nearly on the longitudinal stick stops. The pilot gave this configuration a Cooper-Harper rating of 8, and a PIO rating of 5. PIOs of this severity and for this extended period of time did not occur for either the small or no motion configurations.

The average frequency of the PIO in Figure 7 is 3.0 rad/sec (the average in-flight PIO frequency of this

configuration was 2.2 rad/sec). Also shown on the pitch rate and normal acceleration traces are the motions that both the large and small motion configurations would produce for this visual motion.

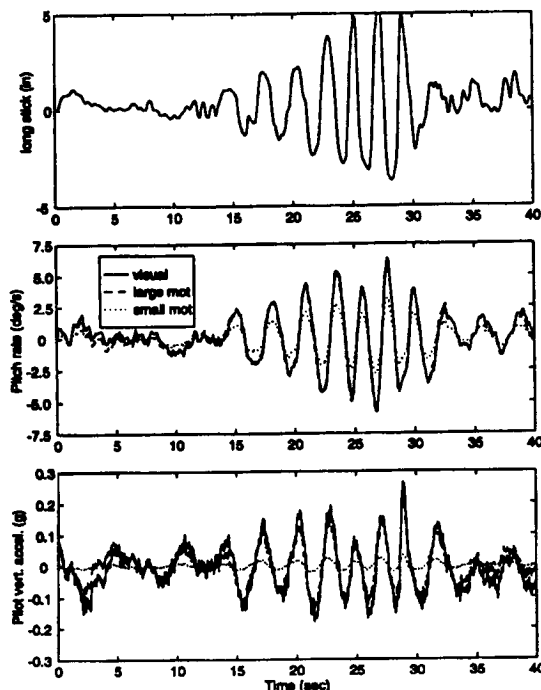


Figure 7 - Example PIO

At the PIO frequency, the large motion configuration provides 100% of the pitch rate cue, and it leads the visual scene by only 5 degs of phase angle. So, the dashed line overlays the solid line. These values may be determined by inserting 3 rad/sec into the motion system filter discussed earlier with the pitch axis parameters (Table 5). The small motion configuration, at best, provides 50% of the visual pitch rate and leads the visual by 6 degs. By motion cueing fidelity standards, both the large and small motion cues are high fidelity.^{10,11}

For the normal acceleration, the large motion configuration provides 80% of the visual cue and leads the visual by 3 degs (this value includes the motion filter and the additional 30 msec of delay that the vertical platform lags the visual). But the small motion configuration provides only 13% of the visual cue and leads the visual by 20 degs. By motion cueing fidelity standards, the large motion cue would be high fidelity, and the small motion cue would be low fidelity. It is for this important acceleration cue that large motion

provides a simulation benefit, and it is likely the reason for the superior performance of the large motion configuration as discussed later.

Landing performance. Longitudinal touchdown position was analyzed using a two-way repeated measures analysis of variance (ANOVA).¹⁷ While statistically significant differences occurred across the aircraft configurations ($F(17,68)=3.73$, $p<0.001$), differences among the motion configurations were not found ($p>0.2$).

Lateral touchdown position was analyzed, and no significant differences were noted among the aircraft ($p>0.4$) or motion configurations ($p>0.4$). Approach airspeed errors were almost always within the desired performance standard.

During the evaluations, it was noticed that pilots had difficulty in judging sink rate during the flare-to-touchdown as less platform motion was presented. Indications of this fact were either harder landings or the safety pilot assuming control for the small and no motion configurations.

Figure 8 shows the means and standard deviations of vertical touchdown velocities for each motion configuration. Each mean is an average of 90 points (18 configurations x 5 pilots). The ANOVA on these data indicated that the motion configuration affected touchdown velocity independent of the vehicle configuration ($F(2,8)=36.8$, $p<0.001$).¹⁷ Aircraft configuration also affected touchdown velocity independent of motion configuration ($F(17,68)=2.93$, $p<0.001$). No interaction between the motion and vehicle configurations was present ($p>0.3$). Thus, touchdown velocity could be modeled as independent functions of the motion and aircraft configurations:

$$h_{td} = f(\text{motion}) + g(\text{aircraft})$$

As more motion was available, pilots were able to lower the touchdown velocity. A previous limited experiment with large motion also indicated this effect when the longitudinal handling qualities were poor;¹⁸ however, the results here indicate that large motion allows lower touchdown velocities regardless of the configuration.

As Table 1 notes, sink rate at touchdown was not a performance parameter in this experiment, which was also the case in the Ref. 3 flight experiment. However, the Ref. 2 simulation experiment added a touchdown performance criterion of ≤ 4 ft/sec for desired performance and ≤ 8 ft/sec for adequate performance. Had that been the case here, it is expected that even further differences among the motion configurations would

have occurred. This is because when more platform motion was added, it compensated for sink rate perception deficiencies in the visual scene.

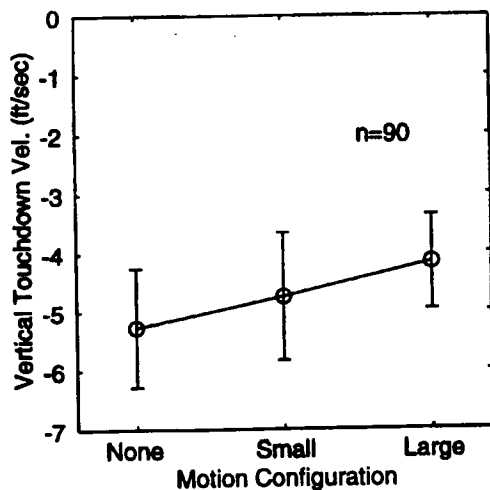


Figure 8 – Touchdown velocities

Safety pilot trips. Figure 9 shows the number of times the automated safety pilot assumed control versus the motion configuration. Over 1400 landings were performed, so the safety pilot assumed control in approximately 10% of the landings. It took control slightly fewer times with small motion than with no motion; however, large motion resulted in significantly fewer safety pilot trips. Many of the safety pilot trips occurred from the inability to judge sink rate.

While it was stated earlier that causing the safety pilot to assume control should raise questions about the configuration's controllability, this seldom occurred. Pilots often felt they were still in control. The issue was that the small or no motion configurations did not assist pilots in their estimation of vertical velocity as did the large motion cues.

Stick activity. Longitudinal stick rms positions were analyzed. Statistical differences occurred across aircraft configurations ($F(17,68)=7.81$, $p<0.001$), with configurations 5-10 and 3-12 having the most activity (0.96 and 0.93 in, respectively). Configurations 2-B and 3-D had the least activity (0.49 and 0.51 in, respectively). No significant differences occurred across the motion configurations ($p>0.1$).

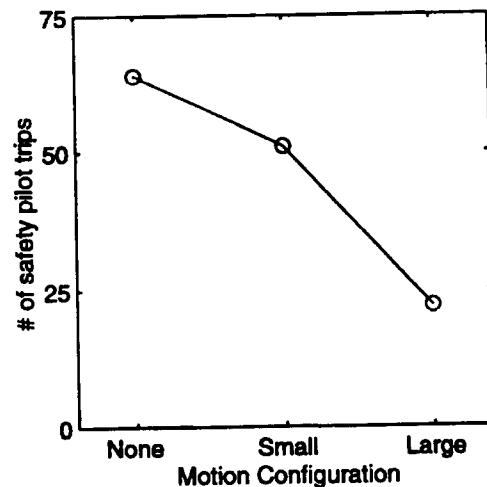


Figure 9 – Safety pilot trips

Handling Qualities Ratings

Large Motion. Figure 10 is a plot of the in-flight HQRs³ versus the simulation HQRs for the large motion condition. If simulation matched flight, then all points would lie on the diagonal line. A 1-unit HQR band is plotted about this line, which is often taken as the range of an acceptable match. Eight of the 18 configurations lie within this 1-unit band. Very similar trends to that of the Ref. 2 fixed-based simulation are noted. That is, the best configurations in flight were slightly worse in simulation, and the worst configurations in flight were better in simulation.

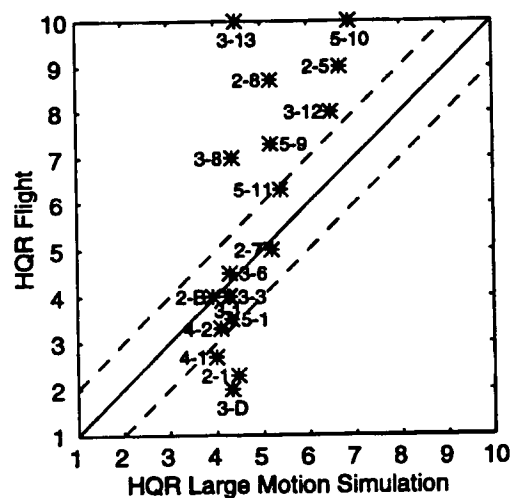


Figure 10 – Flight versus large motion HQRs

Small Motion. Figure 11 shows the in-flight versus simulation HQRs for small motion. Six of the 18 configurations lie within the 1-unit band, which is a degradation from the large motion condition. Again, the same trend on the best and worst configurations existed as for large motion.

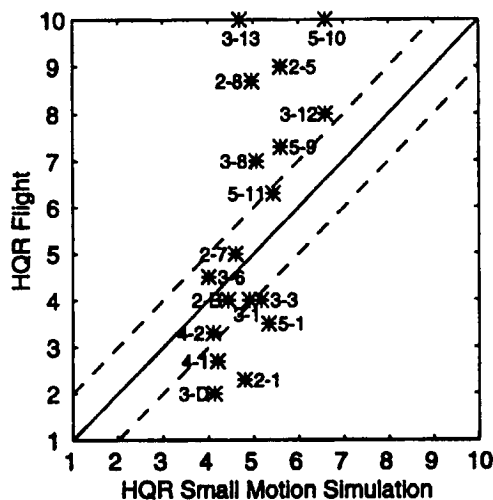


Figure 11 – Flight versus small motion HQRs

No Motion. Figure 12 shows the in-flight versus simulation HQRs for no motion. Five of the 18 configurations were within the 1-unit band, which is a degradation from large motion and small motion. Again, the same trend on the best and worst configurations existed as for large and small motion.

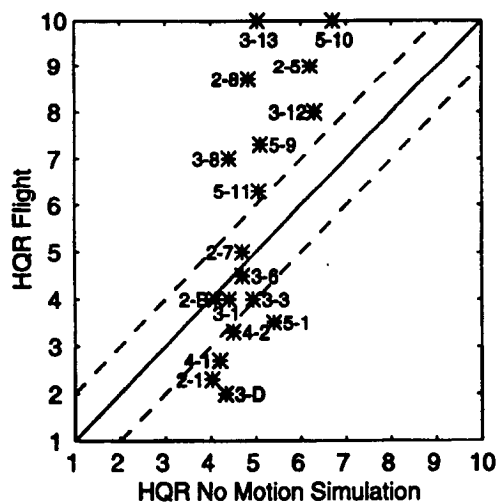


Figure 12 – Flight versus no motion HQRs

Pilot Confidence Factors. Confidence factors of A, B, and C refer to a pilot's opinion that he can assign a handling qualities rating with a high, moderate, or minimum degree of confidence, respectively.¹⁶ Losses of confidence arise when simulation cues are incomplete or inadequate. Figure 13 shows that as more motion is provided, the pilot's confidence in assigning ratings improves. On average, both the no motion and small motion configurations caused the pilot to have less than a moderate degree of confidence in his rating. With large motion, that confidence improved to more than moderate. This difference was statistically significant across the motion configurations ($F(2,8)=5.82$, $p=0.028$). Differences in this measure were not significant across the aircraft configurations ($p>0.1$).

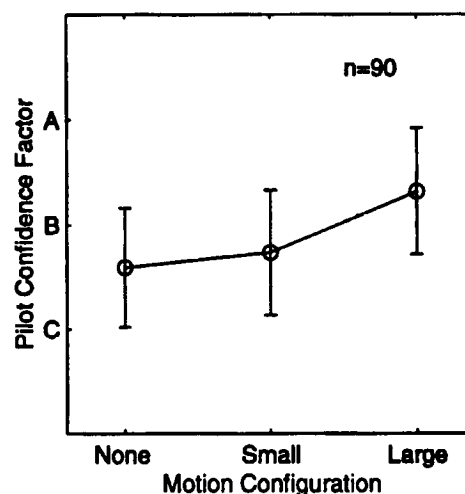


Figure 13 – Pilot confidence factors

PIO Ratings

Large motion. Figure 14 compares pilot-induced oscillation ratings (PIORs) between flight and the large motion simulation. Sixteen of the 18 configurations lie inside the ± 1 PIOR boundary. Except for four configurations, the in-flight PIORs were, on average, higher than the simulation PIORs.

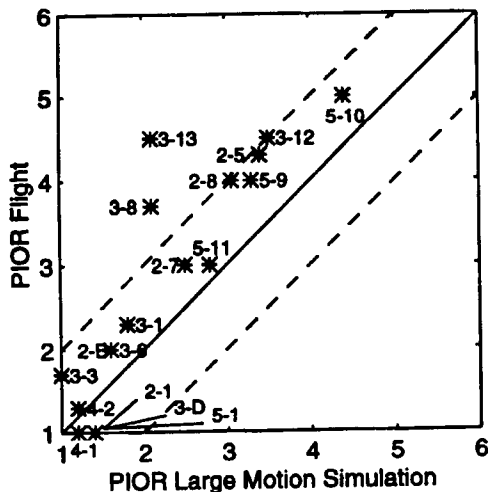


Figure 14 - Flight versus large motion PIORs

Small motion. PIORs for the small motion configuration are shown in Figure 15. Here, 12 configurations were inside the ± 1 PIOR band, which was the worst performance of the motion configurations. Again, except for four configurations, the in-flight PIORs were worse than the simulator PIORs.

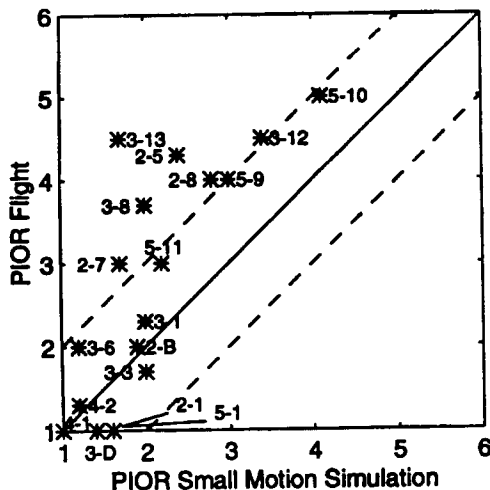


Figure 15 - Flight versus small motion PIORs

No motion. The PIORs for no motion are given in Figure 16. No motion performed slightly better than small motion, but worse than large motion. Fourteen configurations were inside the ± 1 PIOR band. Still, except for four configurations, the in-flight PIORs were higher than the no motion PIORs.

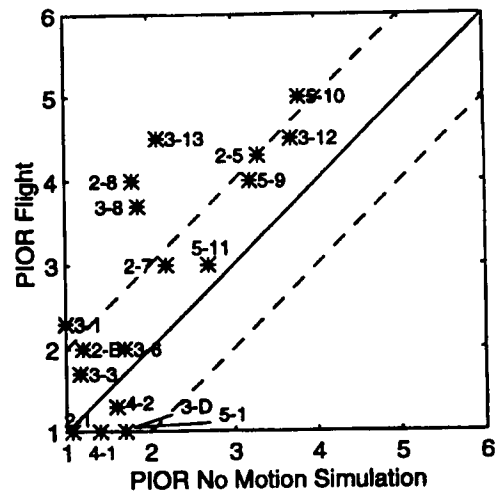


Figure 16 - Flight versus no motion PIORs

Conclusions

A piloted experiment examined the effect of three levels of platform motion displacement on the ability to predict pilot-induced oscillations. Objective and subjective measures were examined for large, small, and no platform motion. The small motion condition represented the displacement of a conventional hexapod platform.

Overall, large motion matched flight more closely than either small or no motion. Specifically, large motion better matched the in-flight pilot-induced oscillation ratings and the handling qualities ratings than did small or no motion. In addition, with large motion, pilots assigned higher confidence factor ratings, achieved lower touchdown velocities, and caused fewer safety pilot trips as compared to the other motion configurations. Finally, only with large motion did markedly divergent pilot-induced oscillations occur.

An example illustrated that high fidelity pitch rate cues were provided by both the large and small motion configurations. However, only large motion allowed high fidelity vertical acceleration cues to be presented. Pilots react strongly to vertical acceleration, and this likely contributed to the large motion configuration providing the best results.

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A Method for the Flight Test Evaluation of PIO Susceptibility

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The handling qualities test method taught at the USAF Test Pilot School is briefly described. This method consists of three parts, or phases: Phase 1 is an evaluation of low bandwidth handling qualities; Phase 2 is an evaluation of high bandwidth handling qualities; and Phase 3 is an evaluation of handling qualities during the operational tasks that make up the design mission of the airplane. Phase 2 high bandwidth testing uses the Handling Qualities During Tracking (HQDT) test technique, which when properly applied has proved remarkably effective in exposing PIO susceptibility in airplanes of every size and shape. For this reason Phase 2 testing is often referred to as a handling qualities "safety gate." If PIO is not experienced during Phase 2 high bandwidth testing, it is unlikely that PIO will be experienced during operational use. If high bandwidth handling qualities are satisfactory, it is unlikely that handling qualities will pose a significant safety of flight concern during operational use.

Introduction The three phase handling qualities test and evaluation method described below has been used at the AFFTC since 1972. When used as described, it has proved remarkably successful as a handling qualities test method and as a means of "optimizing" the flight control system to achieve improved handling qualities. When used in a compromised fashion, it has proved to be correspondingly less successful. The second of the three phases, which centers around high bandwidth Handling Qualities During Tracking (HQDT) testing, has proved especially successful in exposing PIO susceptibility. Unhappily, this valuable tool has often been misunderstood and misapplied, and hence disparaged. Pilots who understand the rationale for high bandwidth HQDT testing, and who have been properly trained in the specialized piloting technique, find it a very effective handling qualities evaluation tool.

Discussion As all of flying qualities testing should be, the three phase handling qualities test method described below is grounded in the model validation test method, which consists of three steps:

1. *Predict the airplane response, based on a model.*
2. *Test the prediction.*

3. *Validate or correct the model, based on the test results.*

The model validation test method is readily recognizable as a form of the scientific method. In Step 1, the handling qualities are *predicted*, using available analytical criteria and piloted simulators. We will not discuss Step 1 in this paper. In Step 2, the airplane handling qualities are *tested* using the three phase test method described below. In Step 3, the handling qualities model is *validated*. We will not discuss Step 3 in this paper. The model validation test method is the most effective, the most efficient, and the safest way to conduct testing. To further emphasize test safety, the handling qualities test method described below is guided by the following procedural rule:

Employ a build-up approach, in which testing progresses from the lowest to the highest level of risk.

To ensure completeness, the handling qualities test method described below is guided by the following principle:

Handling qualities testing should explore the entire spectrum of pilot-vehicle dynamics.

Before proceeding, we pause for two notes.

First, we define handling qualities as the *dynamics, or characteristics, of the pilot plus the airplane*. Second, following the YF-22 PIO incident, we at the Flight Test Center began to refer to PIO as "pilot-in-the-loop" oscillation, rather than "pilot-induced" oscillation. Pilots must be in the loop for a PIO to occur, but pilots do not induce these unwanted oscillations. If anything, it is the airplane that induces them. This is easily shown by noting that the same pilot, flying two different airplanes in the same manner may experience many PIOs in the one but never experience a PIO in the other. When pilots understand that PIO is not their fault, they are more likely to provide objective evaluations, comments, and ratings.

The test method described below is composed of three phases: a low pilot bandwidth phase, a high pilot bandwidth phase, and an operational phase. By "pilot bandwidth" we have in mind both the range of frequencies and the amplitude of control inputs generated by the pilot. "Frequency content" would perhaps be a more descriptive term, but "bandwidth" seems to be more widely used. We will discuss each phase of testing in turn.

Phase 1: Low Bandwidth Testing During Phase 1 testing the pilot conducts an evaluation of low bandwidth handling qualities at safe, up-and-away flight conditions. By low bandwidth handling qualities, we mean the handling qualities characteristics that are associated with relatively smooth (or low frequency), small amplitude pilot inputs. We often refer to Phase 1 testing as "warm-up," or "get acquainted," or "familiarization" testing. Phase 1 low bandwidth testing is designed to introduce the pilot to the airplane under low risk conditions. Phase 1 consists of relatively low bandwidth piloting tasks, including open-loop tasks such as pulse, doublet, and step inputs; semi-closed-loop tasks such as low bandwidth pitch attitude and bank angle captures, steady heading sideslips, and so on; gentle maneuvering in the vicinity of the test airspeed and altitude; and low bandwidth, non-aggressive tracking.

You may object, correctly, that open-loop maneuvers such as pulses, doublets, and steps are not handling qualities test maneuvers at all, because the pilot is not in the loop. We include these maneuvers because they allow the pilot to observe the dynamics, or characteristics, of the *airplane alone* (even though experience shows that an open-loop evaluation may be misleading as an indicator of handling qualities).

Pilots must approach Phase 1 cautiously, even though it is a low bandwidth evaluation. Experience shows that airplanes with less than desirable handling qualities may unexpectedly and quickly draw a pilot into high bandwidth control and PIO. For this reason, pilots must focus on preserving low bandwidth, and be prepared to relinquish control altogether (by freezing or releasing the controls) to arrest an unwanted response such as PIO.

When PIO, or other sufficiently undesirable handling qualities are encountered during Phase 1 low bandwidth testing, strong consideration should be given to correcting these deficiencies before testing progresses to Phase 2 high bandwidth testing.

Phase 2: High Bandwidth Testing During Phase 2 testing the pilot conducts an evaluation of high bandwidth handling qualities. Most of this testing is conducted at safe, up-and-away flight conditions. By high bandwidth handling qualities, we mean the handling qualities characteristics that are associated with aggressive, high frequency, small and large amplitude pilot inputs. Phase 2 consists mainly of HQDT testing. HQDT is perhaps the single most important handling qualities test technique at our disposal, especially when an evaluation of PIO susceptibility is of interest. We often refer to Phase 2 high bandwidth testing as a "safety gate," because experience shows that when this testing is executed correctly and PIO is not exposed, the airplane may be considered PIO-free with near certainty.

There are three principal components of HQDT testing: the piloting technique, the test

maneuver, and the pilot evaluation.

The HQDT Piloting Technique The HQDT piloting technique is a simple one. A small precision aim point is selected on a target. This aim point should not be larger than the pipper or aiming index in the gunsight or head-up display. *The evaluation pilot's task is to track the precision aim point as aggressively and as assiduously as possible, always striving to correct even the smallest of tracking errors as quickly as possible.* The effect of this simple technique is to increase the bandwidth of the pilot's control inputs.

A systematic way to fully explore high bandwidth handling qualities is to begin an HQDT maneuver at low bandwidth (that is, using small amplitude, low frequency inputs); then increase the frequency range using small amplitude inputs; then increase the input amplitude while at high frequency. In practice, you will find that this approach works well for airplanes having satisfactory handling qualities, but not as well for airplanes having less than satisfactory handling qualities. The excessive phase lag associated with degraded handling qualities forces a pilot who is attempting to fly with high bandwidth into a coupled pilot-plus-airplane oscillation at a frequency below what the pilot is capable of achieving. These lower frequency coupled oscillations (which may or may not be PIO) are often a valuable indication that the airplane handling qualities are not what you would like them to be. In other words, the inability to achieve high pilot bandwidth, despite a vigorous attempt to do so, may itself be a sign, in some cases, that the airplane handling qualities are less than satisfactory.

Based on the description given in the preceding two paragraphs, experienced pilots will recognize that the HQDT piloting technique is quite different from the low bandwidth "operational" piloting technique used in normal, everyday flying. In normal everyday flying, experienced pilots do not resort to small amplitude, high frequency inputs, and certainly not to large amplitude, high frequency inputs.

Instead, they prefer small, smooth inputs deftly applied in an effort to anticipate and correct small errors before they grow into large ones. Consider the operational "guns tracking" task, in which an experienced pilot may initially lead the target, then allow the gunsight pipper to drift back to the target (or allow the target to drift up to the pipper). Instead of aggressively correcting tracking errors, relatively smooth, measured corrections are applied with the goal of "floating" the pipper toward the target. A low bandwidth "operational" piloting technique such as this will improve task performance (especially when the handling qualities are less than satisfactory), but it also hides, or masks, the high bandwidth handling qualities of the airplane. The purpose of the HQDT piloting technique is to bring high bandwidth handling qualities characteristics into the open, where they can be evaluated.

Pilots who are unfamiliar with the purpose of Phase 2 high bandwidth handling qualities testing commonly raise several objections to the specialized HQDT piloting technique. One is that it is "unnatural," or "pilots don't fly that way," or "HQDT might be okay for fighters, but not for big airplanes because no one flies big airplanes aggressively." A second objection is that it results in degraded task performance. A third objection is that "I can make any airplane PIO" or "I can make any airplane look bad" by using the HQDT piloting technique. A fourth objection is that "we're only doing this to pacify the engineers." The first objection is largely, but not entirely true; the second objection is true; and the third and fourth objections are untrue. Let's look at each in turn, briefly.

The first objection, that the HQDT piloting technique is "unnatural" in any airplane and is inappropriate for large airplanes, is largely, but not entirely true. Experience shows that the HQDT piloting technique is not *normally* used by pilots, but is an entirely *natural response* when something happens to elevate a pilot's level of excitement or anxiety above a certain threshold. Also, the natural response of a human pilot to high levels of excitement or

anxiety is independent of the size of the airplane. The space shuttle, the C-17, and the B-2 are large airplanes, and each experienced PIOs during testing. The second objection, that the HQDT piloting technique results in degraded task performance, is true. As a practical matter, we observe from operational experience that when excitement or anxiety precipitates a high bandwidth response from a pilot, task performance is degraded. The nature and level of this degraded performance is of interest to us in Phase 2 testing because it is one source of incidents and accidents as well as degraded mission performance. The third objection, which is that "I can make any airplane PIO," or "I can make any airplane look bad" by using the HQDT piloting technique, is false. We show the Test Pilot School students, first using a simulator and then in flight, that a genuinely Level 1 or Level 2 airplane cannot be made to PIO. We show them that a Level 1 airplane will feel crisp and responsive and follow their commands closely even during high bandwidth HQDT testing. They learn by experience that *the HQDT piloting technique will not make a good airplane look bad, but it will make a bad airplane look bad*. This, in a nutshell, is the purpose of Phase 2 handling qualities evaluation: to expose both the good and bad features of high bandwidth handling qualities. The fourth objection, which is that "we're only doing this to pacify the engineers," is also false. Phase 2 testing, as all of handling qualities testing, is conducted for pilots, not for engineers. It is pilots, not engineers, who must fly the airplane, perform the mission (sometimes under very difficult circumstances that are conducive to high pilot bandwidth), and return safely. It is pilots, not engineers, who must live with the consequences when the test community fails to evaluate the full spectrum of handling qualities, or fails to expose every deficiency, or fails to correct deficiencies when warranted.

An interesting feature of the HQDT piloting technique is that, in most cases, the evaluation pilot is not allowed to use the rudder pedals. This is referred to as "feet-on-the-floor" tracking. At the Flight Test Center, experience

has taught us that much can be learned about lateral-directional handling qualities when flying feet-on-the-floor. Pilots are excellent aileron-to-rudder interconnects. When pilots are allowed to use the rudder pedals, they can mask handling qualities deficiencies that might otherwise stand out prominently. However, the HQDT piloting technique should not be thought of as an exclusively feet-on-the-floor technique. There are times when using the rudder pedals is beneficial. For example, the pilot's description of how the rudder pedals were used, together with an analysis of the data, can be helpful in correcting a deficiency.

In HQDT testing the evaluation pilot must not be distracted by the measurement of task performance, such as average tracking error, or time within a given radius of the precision aim point, and so on. Measuring task performance encourages evaluation pilots to abandon or compromise the HQDT piloting technique and reduce their bandwidth. While reduced bandwidth usually results in improved task performance, it also compromises the evaluation of high bandwidth handling qualities. When the HQDT piloting technique is abandoned or compromised, the average test pilot is quite capable of producing good tracking results with a pretty bad airplane. This tells us something about the skills of the pilot, but it doesn't tell us much about high bandwidth handling qualities, which is what we are interested in during Phase 2 testing.

The HQDT piloting technique is not difficult to learn, but it requires practice. The best place to learn and practice this technique is in a flight test simulator. Learning is easier and occurs more rapidly when it is possible to estimate power spectral density functions of the pilot's control inputs immediately after a practice maneuver.

We have noted the importance of large amplitudes and high frequencies in high bandwidth pilot inputs. By "high frequencies" we do not mean that pilots should attempt to track by generating high frequency sinewave

inputs. The high frequency component of high bandwidth inputs comes from the *sharpness*, or *quickness* of the pilots inputs. Sharp, quick, control inputs are produced by reacting to tracking errors as rapidly as possible.

We must emphasize the importance of an honest and vigorous effort to use the specialized, high bandwidth, HQDT piloting technique. Otherwise, high bandwidth handling qualities (which are usually the worst handling qualities) will not be fully evaluated during the test program. Instead, these handling qualities will be evaluated in the field, during operational use by line pilots rather than test pilots.

We conclude our brief description of the specialized HQDT piloting technique by remarking again that this technique, which lies at the heart of Phase 2 high bandwidth testing, is often compromised by pilots and engineers who regard it as unnatural and artificially contrived. In fact, however, this technique is entirely natural under certain circumstances. You need only examine time histories of pilot control inputs during a PIO to see that this is so.

HQDT Test Maneuvers The heart of high bandwidth handling qualities testing lies in the specialized HQDT piloting technique. Any maneuver that requires the evaluation pilot to use the specialized, high bandwidth, HQDT piloting technique is likely to be a suitable HQDT test maneuver. For this reason there is no exclusive catalog of HQDT maneuvers. Maneuvers that have worked well in the past include constant load factor (or angle of attack) air-to-air tracking maneuvers, wind-up turn tracking maneuvers, tracking while closing on the target, tracking in the power approach configuration (with and without closure), air-to-ground tracking, refueling boom tracking, and formation flying. Other maneuvers, perhaps better suited to a particular airplane, may be invented as the need arises.

Formation maneuvers and refueling boom tracking maneuvers should not be flown so close to the lead airplane or to the refueling boom that

the evaluation pilots feel that their safety is compromised by the high bandwidth HQDT piloting technique of aggressive, assiduous tracking.

With a single exception, a fixed pippier or aiming index is used during HQDT testing. When a moving pippier or aiming index is used (as in the case of a computing gunsight), the pippier (or gunsight) dynamics become a part of the evaluation. Our initial goal is to evaluate the dynamics of the pilot plus the airplane, rather than the pilot plus the airplane plus the gunsight. Hence a fixed pippier is nearly always used. The exception arises later, when it might prove desirable to evaluate the effect of the computing gunsight dynamics on handling qualities. Used in this way, HQDT can be an important tool for fine-tuning the gunsight component of the pilot-vehicle dynamics.

The depression angle of the pippier or aiming index is usually dictated by the airplane and the test maneuver. The depression angle may be set to minimize pendulum effect; or set to the angle that would be computed by the gunsight for a given load factor (in air-to-air tracking) or for a given dive angle (in air-to-ground tracking); or set to aid in avoiding the target airplane jetwake.

The test airplane must not be retrimmed during the test maneuver. Trimming detracts from the pilot's concentration on high bandwidth tracking and renders invalid a frequency response analysis of the test data (unless the trim inputs are recorded and made available for analysis).

Pilot Evaluation Pilot evaluation is the third component of Phase 2 HQDT testing. In HQDT testing, pilot comments are the most important part of the pilot evaluation, supported by a PIO rating. Careful and complete pilot comments from HQDT testing are the key to helping designers and flight test engineers understand the high bandwidth handling qualities of the airplane. Cooper-Harper ratings are not assigned following an HQDT evaluation because task performance (such as tracking error) is not measured during HQDT testing. Hence, it is

not possible to assign a legitimate Cooper-Harper rating based on an HQDT evaluation.

Phase 3: Operational Testing During Phase 3 testing the pilot conducts an operational evaluation of the airplane handling qualities. The purpose of Phase 3 testing is to determine whether the handling qualities are suitable for performing the various tasks that make up the design mission. Depending on the airplane, these tasks may include take-off, landing, aerial refueling, formation flight, and air-to-air and air-to-ground weapons delivery. Phase 3 operational testing must often be conducted in the presence of aggravating factors such as atmospheric turbulence, darkness, proximity to the ground, and so on. The risks associated with these factors must be explored in a build-up fashion. Cooper-Harper ratings are appropriate during Phase 3 operational testing.

Conclusion The overarching objective of the three phases of testing we have briefly described is to completely evaluate the full spectrum of airplane handling qualities. When we fail to achieve this objective, operational pilots become test pilots by default, but without the necessary preparation and safeguards we bring to bear in a properly conducted flight test program. For this reason, *the entire range of handling qualities must be explored by test pilots during flight testing, rather than by operational pilots during operational use of the airplane.*

At present, Phase 2 high bandwidth testing using HQDT test techniques is perhaps the most important tool we have for evaluating high bandwidth handling qualities characteristics, particularly PIO susceptibility. HQDT testing is often resisted or disparaged because its purpose and rationale are not understood, or because it has been used incorrectly by pilots who were not properly trained in the specialized HQDT piloting technique. When used properly, HQDT has proved to be uniquely successful. Properly conducted Phase 2 high bandwidth HQDT testing serves as a handling qualities "safety gate." If high bandwidth handling qualities prove to be satisfactory, it is unlikely that

handling qualities will pose a significant safety of flight concern during operational use of the airplane. If PIO is not experienced during HQDT testing, it is unlikely that it will occur during operational use.

Pilot Opinion Ratings and PIO

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Two simple measures for dramatically improving the assessment of PIO susceptibility are presented, together with supporting arguments. These measures are first, to welcome, rather than suppress, the exposure of PIO susceptibility; and second, to assign a Cooper-Harper rating of 10 to every PIO, whether fully developed or incipient. A Cooper-Harper rating of 10 is a declaration that the airplane is uncontrollable during a PIO. It is argued that such a declaration is reasonable because pilots must *necessarily* relinquish control, if only temporarily, in order to arrest a PIO.

Discussion For more than 25 years, it has been possible to obtain reliable flight test assessments of PIO susceptibility using available test methods and rating scales. Yet reliable assessments are not the rule. We believe they could be made the rule by adopting two simple measures:

1. *Welcome, rather than suppress, the exposure of PIO susceptibility.*
2. *Assign a Cooper-Harper rating of 10 to every PIO, whether fully developed or incipient.*

We grant that adopting these two measures would require overturning long standing, deeply ingrained practice. But our experience suggests that traditional practice is misguided and counter-productive. We will discuss each of these proposed measures in turn.

Welcome the Exposure of PIO Susceptibility PIO is not welcome during a flight test program. Consequently, pilots are under subtle but significant informal pressures to ignore, overlook, play down, or explain away occurrences of PIO. The reasons for these pressures are well known: a strong desire to maintain a success-oriented test schedule and budget; the fear of Congressional scrutiny; the fear that Congress will cancel a needed airplane, and so on. Because of these pressures an encounter with PIO can, in our experience, lead to a variety of pilot assessments. If the airplane

is damaged or lost, the pilot would likely agree that a PIO occurred and a Cooper-Harper rating of 10 might be assigned (although in flight testing such a rating is uncommon). If the airplane is not damaged or lost, the pilot might not mention the PIO at all. Or the pilot might initially acknowledge that a PIO occurred, but later deny it. Or the pilot might acknowledge the PIO, but blame it on himself. (How many times have experienced handling qualities testers heard a pilot say: "I screwed up. If I hadn't ..., I wouldn't have gotten into a PIO.") Occasionally, a pilot will acknowledge the PIO and suggest that the airplane needs to be fixed, but the pilot who offers this assessment often suffers for his honesty.

We believe that the discovery of handling qualities deficiencies of every kind, including PIO, should be welcomed. The purpose of an acquisition program is to provide the operational users with an airplane that is suitable for performing the various tasks that make up the design mission. Line pilots rely on the test community to evaluate handling qualities thoroughly and objectively. They rely on the acquisition community to correct those deficiencies that warrant correcting (those that render the airplane unsafe or less than suitable). But these deficiencies cannot be corrected if they have not been found, or have been ignored or played down. Handling qualities deficiencies should be discovered by test pilots during the test program, not by line pilots during operational use. Test pilots should be given to

understand that it is part of their job to discover strengths *and* deficiencies, and they should be lauded when they do. The discovery of an important deficiency should be regarded as an opportunity to provide a better finished product.

We should note in passing that following the YF-22 PIO incident, we at the Flight Test Center began to refer to PIO as "pilot-in-the-loop" oscillation, rather than "pilot-induced" oscillation. Pilots must be in the loop for a PIO to occur, but pilots *do not* induce these unwanted oscillations. If anything, it is the airplane that induces them. This is easily shown by noting that the same pilot, flying two different airplanes in the same manner may experience many PIOs in the one but never experience a PIO in the other. When pilots understand that PIO is not their fault, they are more likely to report occurrences of PIO and provide objective evaluations, comments, and ratings.

At present, PIO susceptibility is not always adequately explored and reported because test pilots and engineers recognize that PIOs are not welcome news. Perhaps the most effective way to immediately improve the assessment of PIO susceptibility is to welcome encounters with PIO during flight testing.

Assign Cooper-Harper Ratings of 10 to Every PIO We believe every PIO, whether fully developed or incipient, should be assigned a Cooper-Harper rating of 10. This is equivalent to saying that every PIO, whether fully developed or incipient, represents at least a temporary loss of control. We define fully developed and incipient PIOs in the following way. A fully developed PIO is one in which several cycles of the oscillation occur, even though the oscillation may not reach a visibly steady state. An incipient PIO is one which the pilot is able to recognize and quickly arrest, perhaps within a cycle or less.

Some in the handling qualities flight test community would agree that a fully developed PIO indicates a loss of control, and therefore

warrants a Cooper-Harper rating of 10. But many would disagree, contending that when the pilot is able to arrest a fully developed PIO and continue with the task, control has not been lost, at least not in a long term, or global sense. They would further contend that a Cooper-Harper rating of 10 is warranted only when the PIO results in a stall, departure, collision with another airplane or the ground, or complete abandonment of the task. Few in the test community would agree that an incipient PIO warrants a Cooper-Harper rating of 10. If it can be shown that both fully developed and incipient PIOs represent a loss of control, then perhaps we can agree that every PIO should be assigned a Cooper-Harper rating of 10. We will turn our attention first to fully developed PIO, then to incipient PIO.

Fully Developed PIO Let us first explore the question of whether a fully developed PIO represents a loss of control. We begin by asking how a pilot arrests a fully developed PIO. One of three methods is usually employed: the pilot either freezes the controls, or releases the controls, or significantly reduces bandwidth (or the aggressiveness of control). When a pilot freezes or releases the controls, he has clearly relinquished control of the airplane for a time sufficient to arrest the PIO. Does it not follow that the pilot has also abandoned the task during the time required to arrest the PIO? While the controls are frozen or released, the pilot cannot be tracking the target, or controlling the flare, or whatever. If this is the case, we may ask why the pilot has abandoned the task if he still has control over the airplane. Isn't the answer that the airplane was uncontrollable during the PIO? When a pilot significantly reduces bandwidth to arrest a PIO, we would suggest that he has, in effect, transitioned from the primary task (tracking, landing, refueling, and so on) to the suddenly more important task of *regaining* control. We would even suggest that significantly reducing bandwidth is really another form of temporarily freezing the controls.

Implicit in our discussion is the understanding

that when a pilot temporarily relinquishes control to arrest a PIO, he does so as a matter of necessity rather than choice. If it is *necessary* for the pilot to relinquish control in order to arrest a PIO and reestablish control, aren't we acknowledging that the airplane was temporarily uncontrollable? If the airplane was controllable, why did the pilot find it *necessary* to relinquish control?

Nevertheless, the objection will be raised that if a task is performed one hundred times and PIO is encountered only once, it would be silly to claim that the airplane is uncontrollable. We believe the proper rejoinder to this objection is a reminder that Cooper-Harper ratings are assigned to individual evaluations, or trials. If a PIO was experienced only once in one hundred evaluations of the same task in the same configuration at the same flight conditions, we would argue that the pilot lost control only once in one hundred evaluations, and that the airplane proved to be uncontrollable only once in one hundred evaluations, so that a rating of 10 was warranted only once in one hundred evaluations. This one data point out of a hundred is an important one that should not be swept under the rug or played down. If it can happen to a test pilot once in a hundred times, how often is it likely to happen to less experienced and possibly less skilled line pilots?

Incipient PIO Now let us turn our attention to the question of whether an incipient PIO represents a loss of control. In Figure 1 we present a sketch comparing time histories of pitch rate response and stick force during two events of interest. In one event, represented by dashed line time histories, we see a fully developed PIO. In the second event, represented by solid line time histories, we see an incipient PIO. Both PIOs were precipitated by identical circumstances. At the first arrow, nose down pitch rate begins to develop and the pilot counters by nudging the stick aft, but without apparent effect (perhaps because of excessive phase lag), so that nose down pitch rate continues to increase. The pilot continues to smoothly increase countering stick force until,

suddenly, at the second arrow the airplane begins to pitch up rapidly. In an attempt to arrest this rapid and unsettling reversal of motion the pilot takes action. In the PIO represented by the dashed line time histories, the pilot makes a moderately large and rapid control input in the opposite direction, which aggravates the airplane response and causes the pilot to transition from low to high bandwidth control. A fully developed PIO ensues. In the PIO represented by the solid line time histories, the pilot adopts a different course of action. Recognizing that a PIO is about to begin, the pilot makes a small corrective input to arrest the unwanted motion and then relinquishes control by freezing the stick. After a short interval (perhaps a second or two, perhaps only a fraction of a second), the pilot gets back into the loop and resumes flying the airplane. Note that there is no visible evidence of PIO or PIO susceptibility in the solid line time histories of this incipient PIO. Only the pilot is aware that he intentionally relinquished control in order to avoid the PIO he sensed was about to ensnare him. When flying an airplane that is PIO susceptible, it is not uncommon for pilots to repeatedly relinquish control to forestall PIO.

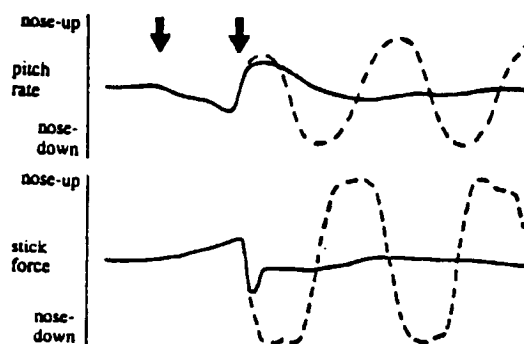


Figure 1 A comparison of two events.

What distinguishes the events recorded in the dashed line time histories from those recorded in the solid line time histories? In the dashed line time histories, the pilot remained in the loop and allowed himself to be drawn from low bandwidth control into high bandwidth control, resulting in a fully developed PIO. In the solid

line time histories the pilot made a small corrective input and then temporarily relinquished control of the airplane until the unsettling motion subsided, thereby avoiding any visible evidence of PIO or PIO susceptibility. But we see in this second case that the pilot *did* embark on a PIO, before quickly arresting it by temporarily relinquishing control. In other words, a PIO was encountered in both cases: in the one, the PIO became fully developed, whereas in the other the PIO was incipient. In both cases, we believe the airplane should be described as PIO susceptible.

Most pilots and engineers would argue that the event recorded by the solid line time histories in Figure 1 is simply an example of pilot compensation, and indeed we acknowledge that this is so. By temporarily relinquishing control (a form of compensation), the pilot succeeded in arresting the PIO at the incipient stage, before it could become fully developed. As every experienced pilot knows, when an airplane has poor handling qualities, temporarily relinquishing control can be a very effective form of pilot compensation. Skilled, experienced pilots know when to exercise control and when to leave well enough alone. When poor handling qualities are in evidence, it has been observed that the best pilots are those who exercise the most forethought and the least control. Unfortunately, this form of compensation may hide serious deficiencies from everyone but the pilot, who may choose not to mention them. Our concern is that, by regarding the temporary relinquishing of control as compensation, the pilot is hiding the fact that an airplane is PIO susceptible. We believe that when control must, *of necessity*, be temporarily relinquished to arrest or forestall PIO, whether incipient or fully developed, the airplane must be regarded as temporarily uncontrollable. To regard it otherwise is to risk assessing the PIO susceptibility of pilots rather than airplanes.

Conclusion For more than 25 years, it has been possible to obtain reliable flight test assessments of PIO susceptibility using available test methods and rating scales. However, many

pilots and engineers have deduced from flight test practices that PIO encounters are unwelcome. Available test methods and rating scales are not always used, or are used in a compromising manner, rendering them less effective; and subtle pressures may be brought to bear on pilots, encouraging them to ignore, overlook, play down, or explain away PIO encounters. We are presently quite capable of thoroughly and accurately assessing PIO susceptibility, but we believe that such assessments will not become routine until two simple measures are adopted: first, welcome the exposure of PIO; and second, assign a Cooper-Harper rating of 10 to every encounter with a PIO, whether fully developed or incipient.

To some, it will seem Procrustean to insist that every occurrence of PIO be assigned a Cooper-Harper rating of 10. After all, this is a declaration that the airplane is uncontrollable, which is a harsh word. Nevertheless, the strategy for arresting a PIO is to temporarily relinquish control, which leads us to the question: if an airplane is controllable, why should it ever be *necessary* to relinquish control? When control is given up of *necessity*, doesn't this mean that the airplane could not be controlled, and is therefore uncontrollable, even if only temporarily? Although the strategy of temporarily relinquishing short term control in order to preserve long term control may legitimately be described as pilot compensation, doing so serves to camouflage PIO susceptibility. The pilot may recognize what he is doing, but he is unlikely to mention it to anyone else.

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